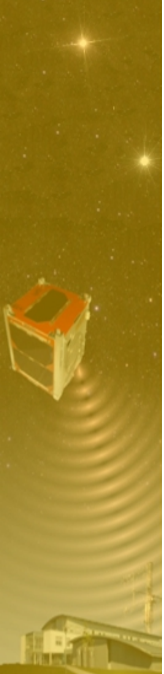

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Intelligent Analysis of Medical Data in a Generic Telemedicine Infrastructure

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Intelligent analysis of medical data in a generic telemedicine infrastructure

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Abstract

Telemedicine uses telecommunication and information technology to provide health care services over spatial distances. In the upcoming demographic changes towards an older average population age, especially rural areas suffer from a decreasing doctor to patient ratio as well as a limited amount of available medical specialists in acceptable distance. These areas could benefit the most from telemedicine applications as they are known to improve access to medical services, medical expertise and can also help to mitigate critical or emergency situations. Although the possibilities of telemedicine applications exist in the entire range of healthcare, current systems focus on one specific disease while using dedicated hardware to connect the patient with the supervising telemedicine center.

This thesis describes the development of a telemedical system which follows a new generic design approach. This bridges the gap of existing approaches that only tackle one specific application. The proposed system on the contrary aims at supporting as many diseases and use cases as possible by taking all the stakeholders into account at the same time. To address the usability and acceptance of the system it is designed to use standardized hardware like commercial medical sensors and smartphones for collecting medical data of the patients and transmitting them to the telemedical center. The smartphone can also act as interface to the patient for health questionnaires or feedback. The system can handle the collection and transport of medical data, analysis and visualization of the data as well as providing a real time communication with video and audio between the users. On top of the generic telemedical framework the issue of scalability is addressed by integrating a rule-based analysis tool for the medical data. Rules can be easily created by medical personnel via a visual editor and can be personalized for each patient. The rule-based analysis tool is extended by multiple options for visualization of the data, mechanisms to handle complex rules and options for performing actions like raising alarms or sending automated messages.

It is sometimes hard for the medical experts to formulate their knowledge into rules and there may be information in the medical data that is not yet known. This is why a machine learning module was integrated into the system. It uses the incoming medical data of the patients to learn new rules that are then presented to the medical personnel for inspection. This is in line with European legislation where the human still needs to be in charge of such decisions. Overall, we were able to show the benefit of the generic approach by evaluating it in three completely different medical use cases derived from specific application needs: monitoring of COPD (chronic obstructive pulmonary disease) patients, support of patients performing dialysis at home and councils of intensive-care experts. In addition the system was used for a non-medical use case: monitoring and optimization of industrial machines and robots. In all of the mentioned cases, we were able to prove the robustness of the generic approach with real users of the corresponding domain. This is why we can propose this approach for future development of telemedical systems.

"A person's words can be life-giving water;
words of true wisdom are as refreshing as a bubbling brook."

Proverbs 18:4

"We can turn a heart with the words we say.
Mountains crumble with every syllable,
hope can live or die.
So speak Life!"

Toby McKeehan

Contents

Chapter 1

Introduction

1.1 Motivation

In industrialized countries the change in the demographic structure leads to increased needs in health care. Thus, for the year 2050 the expected percentage of people over 65 years in the total population is in Japan about 38%, in Western Europe 29%, in USA about 22%, while in 1950 corresponding numbers were below 10% [1]. The development of the age distribution in Germany is depicted in figure 1.1. The numbers that were taken in 2015 are used to predict the values of 2017 (middle graph) and 2045 (right graph) in comparison to 1980 (left graph). While people get older they suffer from diseases that occur especially in higher ages. The health care systems of western societies are challenged with a lot of problems caused by these developments of the demographic structures and their implications on the quality of medical treatments. Although medical science is progressing, it cannot even out the higher amounts of patients that generate a higher demand for medical supervision. In addition, it becomes more and more difficult to provide an adequate medical coverage of rural areas with low population density. Qualified personnel is more attracted to areas with higher population density so that rural areas sustain a skill shortage in medical professions [2][3][4][5]. Furthermore, the health care system is under enormous pressure because of the rising number of patients with chronic diseases. The treatments of these chronic diseases often require special machines and a lot of supervision by medical personnel, which leads to even faster increasing costs for the health care system. The combination of the aging population and the rural depopulation leads to a high demand for changes to the health care sector and the development of assistive technologies. The significant increase of capabilities in modern telecommunication and data processing enables advanced tele-service solutions to assist medical treatment at remote locations. These emerging telemedicine systems promise to increase treatment quality, lower hospitalization times and reduce the need of medication by allowing a continuous monitoring of the patients health status. This trend promotes the development of telemedical systems that are capable to provide a fast and high quality medical treatment to a broad amount of patients while covering broad areas (fig. 1.2). To get a high acceptance from both patients and medical personnel, the system has to be flexible, easy to use, reduce the workload of the medical personnel and involve the patient into the treatment. The bridging of the spatial distance between patient and medical personnel makes more

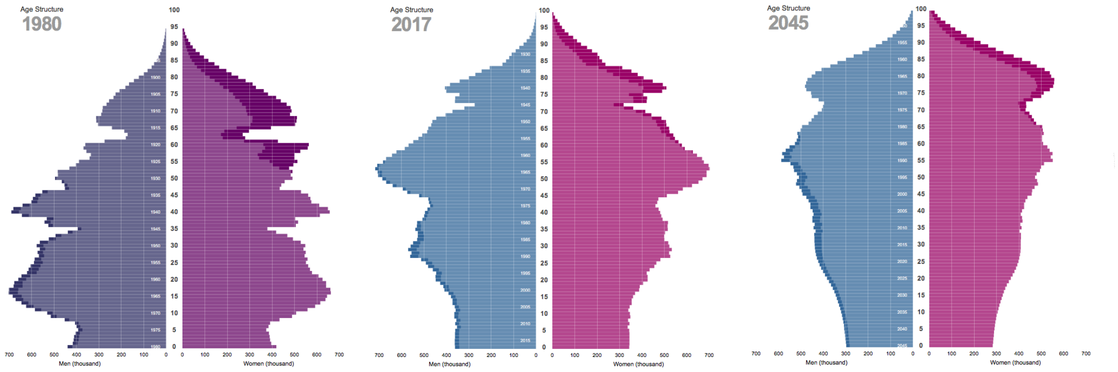


Figure 1.1: Age distribution in Germany 1980, 2017 and prognosis for 2040 [6]

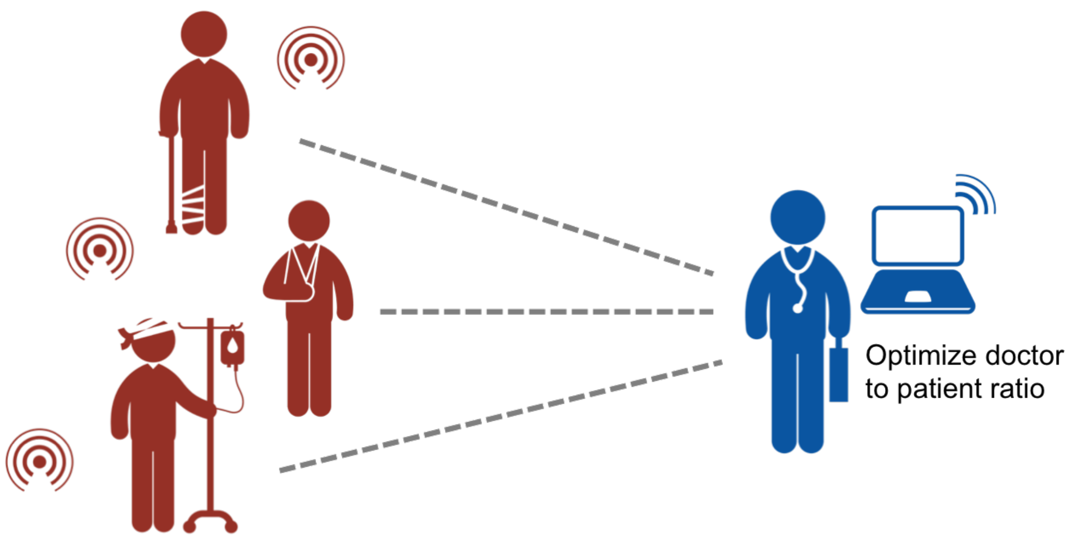


Figure 1.2: Increase doctor-to-patient ratio and therapy quality

regular consultations possible (cf. figure 1.3). The intervals between the consultations can be shortened, which allows fast recognition of progressing diseases. The dense monitoring prevents critical events and saves time and cost intensive treatments. As travel times are eliminated the physicians can treat more patients than before. Progress of telematics (=Telecommunication + Automation + Informatics)

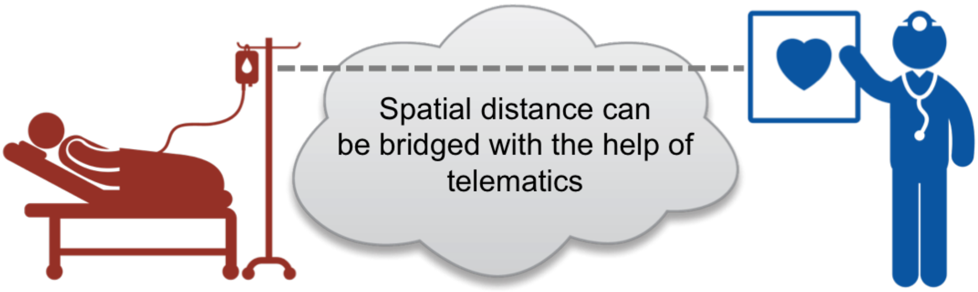


Figure 1.3: Bridge the spatial distance between patient and doctor

[7] used in telemedicine applications promise increasing quality of the treatment at reduced costs. In addition, medical sensors experience fast enhancements and are often available as commercial off-the-shelf (COTS) hardware that can be used by the patients themselves. Beside the development of new network technologies, smartphones offer a lot of new possibilities for innovative products. There are advantages like the possibility to communicate with sensors over the personal area network, store data, pre-process data and communicate over wide area networks in one device. These make the smartphone an interesting opportunity especially in tele-health applications. Another advantage is the growing occurrence of smartphones in the population. Studies show a rise of smartphone users in Germany of about 100% between 2010 and 2012 [8]. Using smartphones with all its advantages, a multi-agent-based system can be set up which can assist in better health-care in the ways described by Mazzi et al. [9], where software agents were used to interact with the patients and initiate a consultation with the doctor when an indication is given. The current development in machine learning and data mining technologies also promise very interesting applications in medical use cases. The possibilities range from intelligent filtering of medical data to automatic analysis in order to present a diagnosis. Promising results, like workload reduction for medical personnel or accurate predictions of a diseases progress would be possible. Since there are very strict legal limits in Germany regarding the use of personal data or generating a diagnosis, the development is difficult. The lower initial acceptance of medical professionals and patients for such a system has to be considered. Sometimes this can lead to a low compliance on both sides.

1.2 Topic description

This thesis describes the development, evaluation and extension of a generic telemedicine framework. The system is built upon requirements that were defined in the research projects “Telemedicine: Remote care at chronic obstructive pulmonary disease (COPD) and home respiration”, “Telemedicine: Support of the autonomy of dialysis patients through telematic methods” (both funded by the German Federal Ministry of Education and Research, BMBF, project grant No. 01EX1014F and 01EX1014G) and “Tele intensive care” (funded by the Bavarian Ministry of Health). By developing the different modules and integrating them into one system we tried to cope with the research questions listed above. Figure 1.4 provides a high level overview of the different components of the telemedicine framework. The patient is equipped with medical sensors and a smartphone, that collects and transmits the data. It also acts as the interface to the system for the patient. The medical personnel can interact with the patient directly, using the provided interfaces. Additionally, they have access to the data storage or can perform analysis on the data. Every communication link is secured to protect the privacy and safety of the patients. Data transmission strategies are adapted to the current link stability and bandwidth. The backend manages all the data collection, aggregation and analysis tasks. It also provides many interfaces to export data or interact with the users or other stakeholders of the system, like caregivers or other clinical staff. This work presents a generic and extendable telematic infrastructure which allows flexible telemedicine for patients with different diseases. For the development of the system the requirements of two different disease treatments with high relevance for the health care systems of western societies are analyzed: COPD and dialysis. The telemedical system consists of many devices like sensors and smartphones that have to be included into a network to transmit and receive the current patient and treatment status. To integrate all devices into the network structure a lot of parameters and aspects have to be considered. Altogether this system offers the opportunity for improvements of the medical treatment of the patient and simultaneously a reduction of costs.

For the example cases of COPD, dialysis and intensive care a specific sensor equipment to characterize the health status, as well as equipment for continuous and safe data transmission and communication are presented. Data processing at a tele-service center has to filter information, such that only the critical cases are confronted to the doctors. Challenges, system architecture and first experiences of this telemedicine approach for remote monitoring of patients are reported. The following chapter provides a survey of the solutions at various medical fields. Subsequently, details about specific telematic solutions for the context of pulmonary diseases and of dialysis are emphasized.

To meet the data analysis requirements we built up a telemedical system that uses a rule-based approach to provide intelligent assistance for the physician and a smart component for the patient that can adapt to changing environments and give feedback about the treatment to the patient. The data analysis module, like

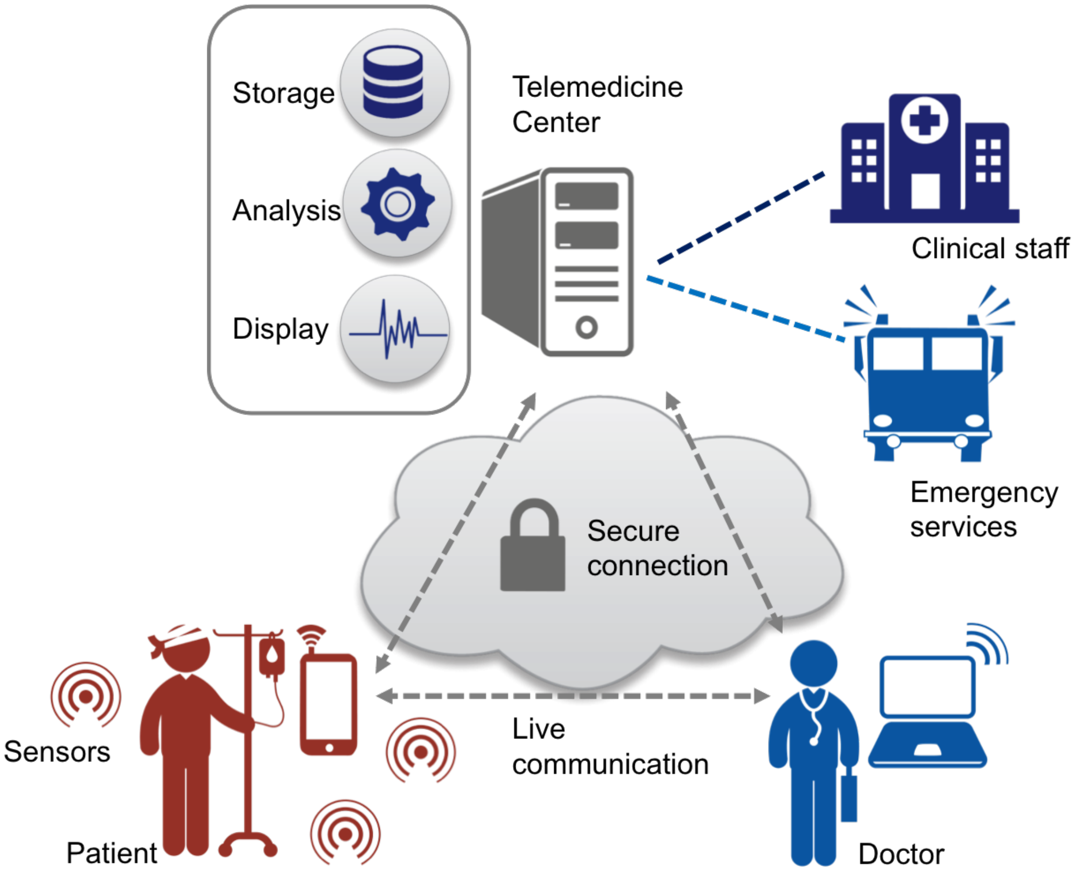


Figure 1.4: Generic telemedicine infrastructure

depicted in figure 1.5, is a part of the telemedical framework. The Telemedical Applications with Rule based Decision- and Information-Systems (TARDIS) framework continuously analyzes data from the patients device according to rules, that can be adapted and supplemented by the users. The analysis can be used to create data visualization, detect anomalies or events in the data or to predict upcoming events. The system is held flexible, modular and platform independent to allow reusing the system in other fields of application such as industrial tele-maintenance.

In the research field of telemedicine there are still many open questions and challenges. As medicine is a large area that influences many other fields, the demands to telemedicine are versatile too. The questions and problems can be divided into categories like medical, technical, economic, ethical, legal and organizational questions [10]. We picked some challenges to focus our work on that are mainly of technical matter:

- How can the spatial distance between patient and supervising medical personnel be bridged efficiently?
- Can the decreasing doctor-to-patient ratio be compensated by the use of telemedicine?
- What is necessary to transfer the expert knowledge to the place where it is needed?
- What can be done to lower the technical and financial gaps for the broad use of telemedicine?
- Are COTS products suitable to be used for tele-health?
- Which network and link characteristics are suitable for tele-health applications?
- How can different diseases be treated with the same telemedical infrastructure?
- Which components does a generic telemedicine infrastructure require?
- Can the use of telemedical systems increase the prevention of diseases?
- Does a telemedical system help creating new knowledge about the progress of diseases?

1.3 Summary of contributions

The development of a complete generic telemedical system requires the creation of many different interfaces and modules. We decided to build the system upon three different use cases, consisting of COPD, dialysis and intensive care. As healthcare is a rather new field for application of telematics we had to evaluate the available

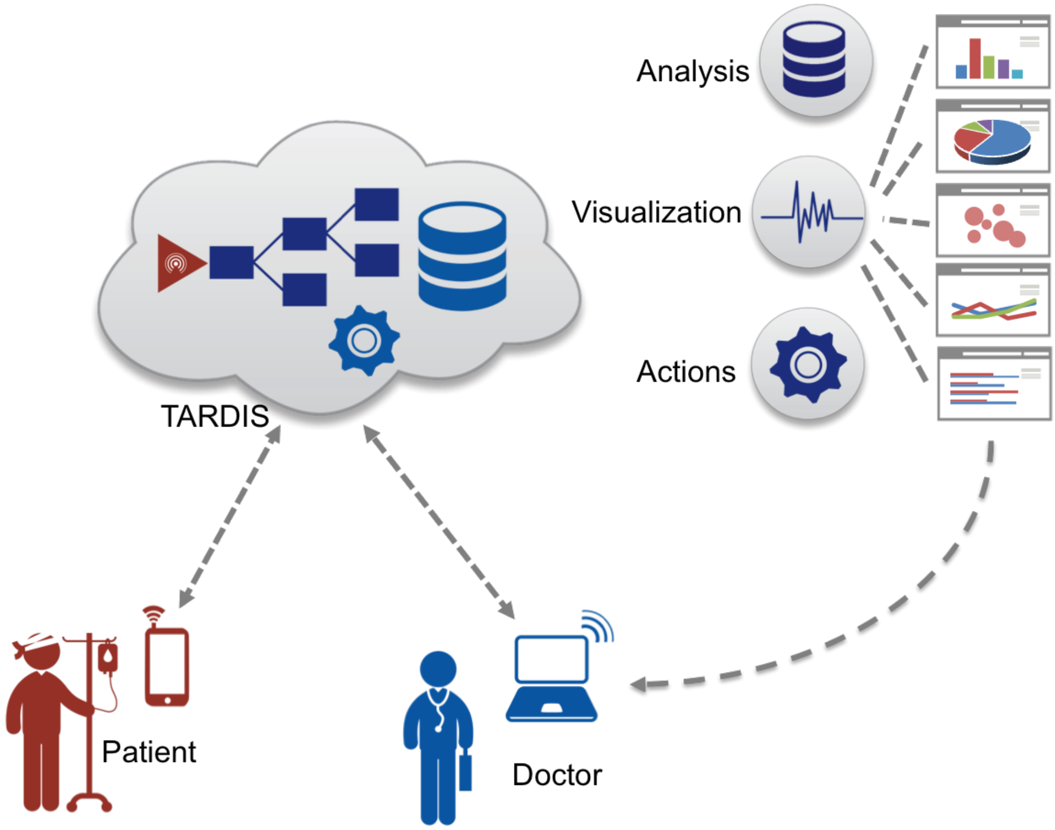


Figure 1.5: Intelligent analysis of medical data for prevention and generating new medical insights

techniques for their suitability for healthcare. This thesis describes the different modules that were created to form a generic telemedical system. The contributions to the international research are as follows:

- Analysis of the link quality of different communication techniques, divided into near-field communication, local area communication and wide area communication links. This analysis is a starting point to evaluate if specific communication applications or data transfer can be handled properly over a specific link type with regard to tele-health applications [11].
- Design and architecture of a generic telemedicine system for remote supervision of patients in their homes [12].
- Creation and evaluation of interfaces for every participant of the system [13].
- Evaluation of the developed system in cooperation with medical personnel, patients and medical engineers [14].
- Implementation of a rule based decision framework designed to reduce the workload of medical personnel [15].
- Extension of the rule based data analysis framework for analyzing industrial machinery data [16].
- Development of a mobile, web-based system for telemedical councils, including data transfer and live video and audio communication [17][18].

1.4 Thesis outline

The remaining parts of this work are structured as follows: Chapter 2 describes some of the methods and techniques that build the basis for this work and intends to provide a better understanding about the surroundings of the different parts of this thesis. It includes the basics of telematics like common issues in telematic systems, communication links and networks. The terms “big data” and “data mining” are introduced including some widespread used methods and fields of application. The different forms of machine learning are identified. As this work is done in a medical context, the methods of data analysis and filtering in this field are highlighted followed by some fundamentals of medical treatment procedures that are relevant for the different use cases. Chapter 3 gives an overview of the related work in the different fields. It lists examples of other systems and research work in this area to give a context frame for this thesis. Chapter 4 presents the developed telemedicine system. The use cases are introduced and their requirements to a telemedical system are investigated. The different modules, their underlaying technology, architecture and design are described. Chapter 5 introduces the rule-based decision system that was integrated into the telemedical system. It allows user specific analysis of the data and automated reactions. Beside the use cases in the medical context the decision system was also used in an industrial context for analysis of machinery data. The related use cases and necessary changes to the system are also part of this chapter. Additionally it is described how rules for the decision system can be derived by the system itself. The process of preprocessing the data, generating rules and integrating the whole process into the framework and work flow is depicted. In chapter 6 a summary as well as final conclusions are given. It also presents some ideas for future research based on this work. The main aspects of this work are also depicted in figure 1.6.

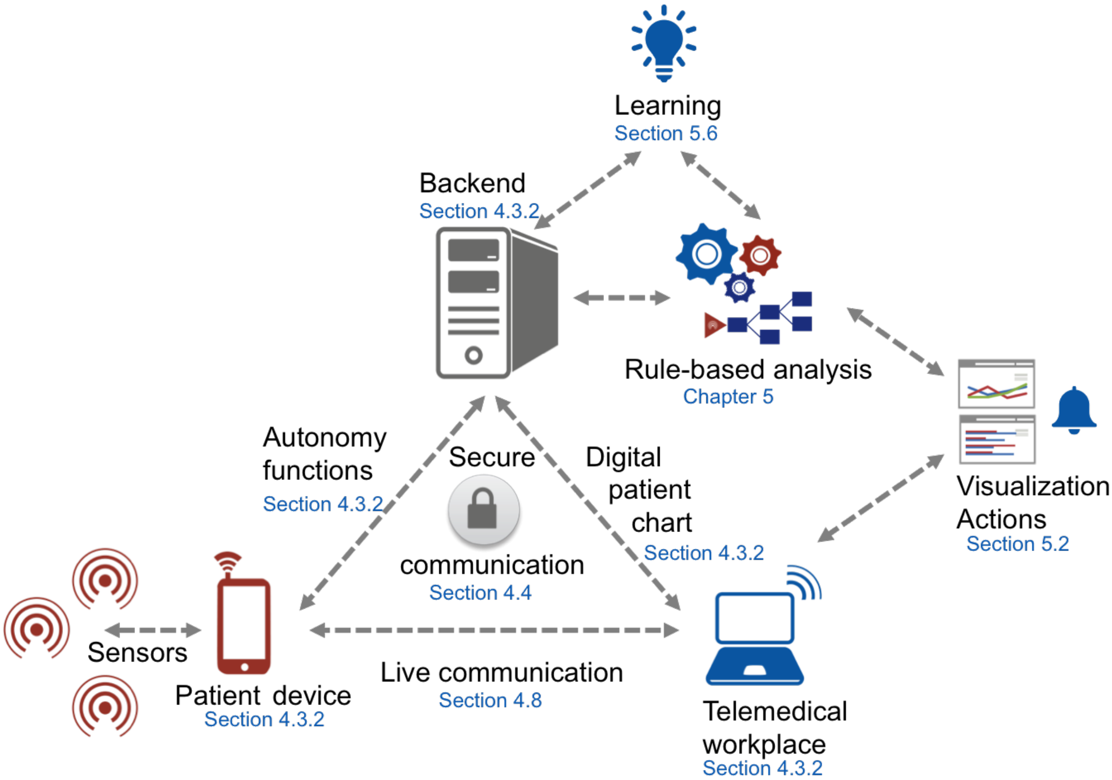


Figure 1.6: Main aspects of the telemedicine system

Chapter 2

Fundamentals

This chapter describe the theory of methods and algorithms used in this work. It should provide a better understanding for the techniques and their context that are mentioned later on.

2.1 Telemedicine

Nowadays, many areas take advantage of the fast progressing information and communication technologies that introduce mobile solutions to all kind of applications. Even in medicine, technology is used to bridge spatial distances and transfer information. These technologies are called “Telematics” which is a combination of the disciplines telecommunication, automation technology and computer science. The principle of telematics is rather old and already discussed in the 70s [7] but it is also the key technology for modern development like Internet-based services, “Industry 4.0” or telemedicine.

The very beginnings of telemedicine lie in the 1960s where physicians used telephones, plain old telephone service (POTS) and later integrated services digital network (ISDN), to discuss the health status of patients or transfer data to others (cf. figure 2.1). Even medical tele-monitoring was realized in the USSR for monitoring and documentation of p-waves in the electrocardiogram (ECG) of cosmonauts. Over time a lot of use-cases emerged, that created the necessity of providing medical services over spatial distances like in offshore areas (e.g. on oil rigs) [19]. The field of telemedicine is often separated into two areas, divided by the services that are provided: tele-monitoring and tele-care [19]. While tele-monitoring is mostly the passive action of collecting vital data from patients and transferring them to medical personnel, tele-care has more active parts like interaction with patients or providing medical treatment. Thus, tele-care closes the feedback loop between patient and supervising personnel. In most modern systems there are both components present.

Tele-monitoring is very useful for patients with chronic diseases where vital parameters can be electronically measured and transferred to the supervising personnel. Patients can stay in their domestic environment which is helpful for rehabilitation. With tele-monitoring even patients with a higher risk level don’t need to stay at the hospital and are still under supervision that can react in case of emergencies [20]. Tele-monitoring is often used for a longterm supervision of patients that had a critical incident and are in risk for further worsening of the health status. The

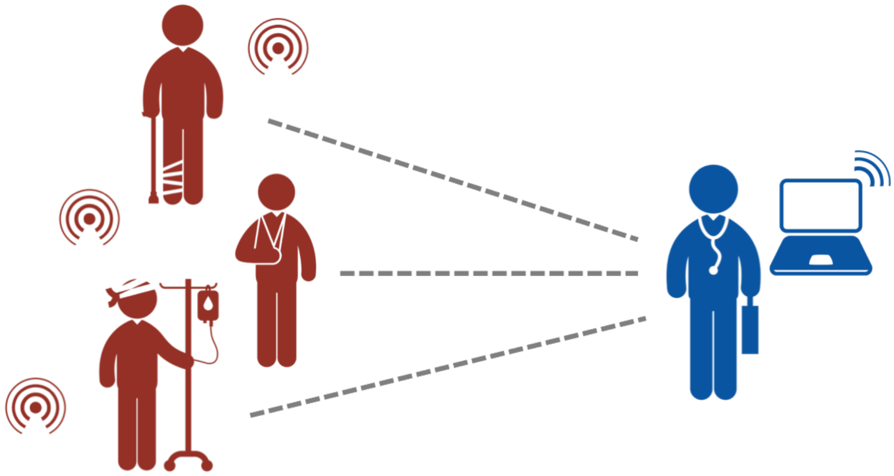


Figure 2.1: Connecting patients and physicians via telemedicine

patients measure vital data on a regular basis and transmit them to a center. In case of irregularities the patients can contact the center where the medical personnel can evaluate the patients' current health status based on the measured vital data. This generates a higher safety for the patient and a feeling of being well supervised [21].

Another distinction of telemedical systems is by identifying the users of the system. There are systems that are intended for use between doctors ("Doc2Doc") or between doctors and their patients ("Doc2Patient") (cf. [22, 23]). Figure 2.2 shows possible stakeholders in telemedicine systems. A goal of telemedicine is to connect all of these parties, from specialists in hospitals, over care providers and patients to relatives. Since medicine always had a humane or social component, there were a lot of doubts that telemedicine could worsen the treatment due to the lack of social interaction between patients and doctors [24]. Recent studies show that this is not the case. Some relations between patients and their supervising physicians even intensified with the use of telemedicine [25].

2.1.1 Signals

In order to describe the signals produced by devices, we distinguish between continuous and digitized data as depicted in figure 2.3. This distinction applies respective to the time axis and also to the value axis. An analog sensor for example generates a time-continuous and value-continuous signal. The process of converting a continuous signal into a numeric sequence is called sampling. The Nyquist-Shannon-Kotelnikov theorem (sampling theorem) states, that a specific minimal sample-rate needs to be used in order to reconstruct the signal perfectly. "If a function $f(t)$ contains no frequencies higher than W cps [counts per second], it is completely determined by giving its ordinates at a series of points spaced $\frac{1}{2}W$ seconds apart." ([26] p. 448) Another important factor is time synchronization: Data processing and data transmission needs time. If more than one device or sensor is used, a time synchronization

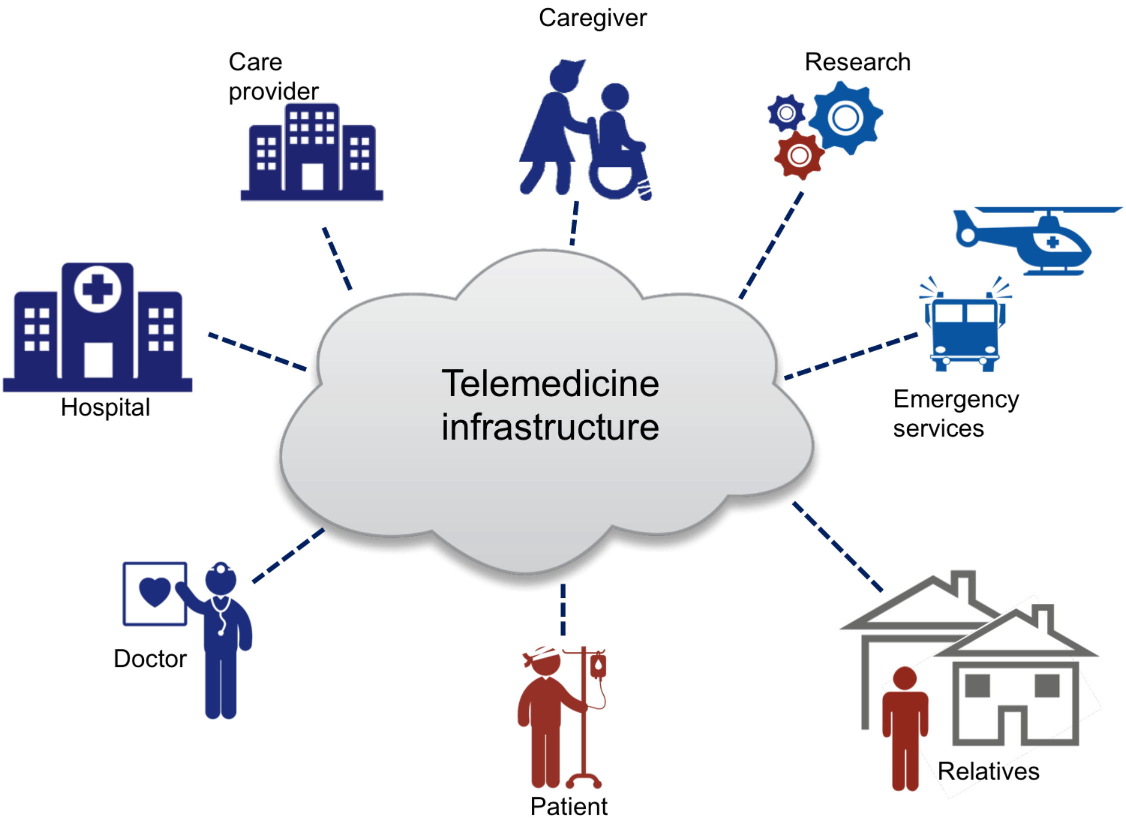


Figure 2.2: Potential stakeholders in telemedicine systems

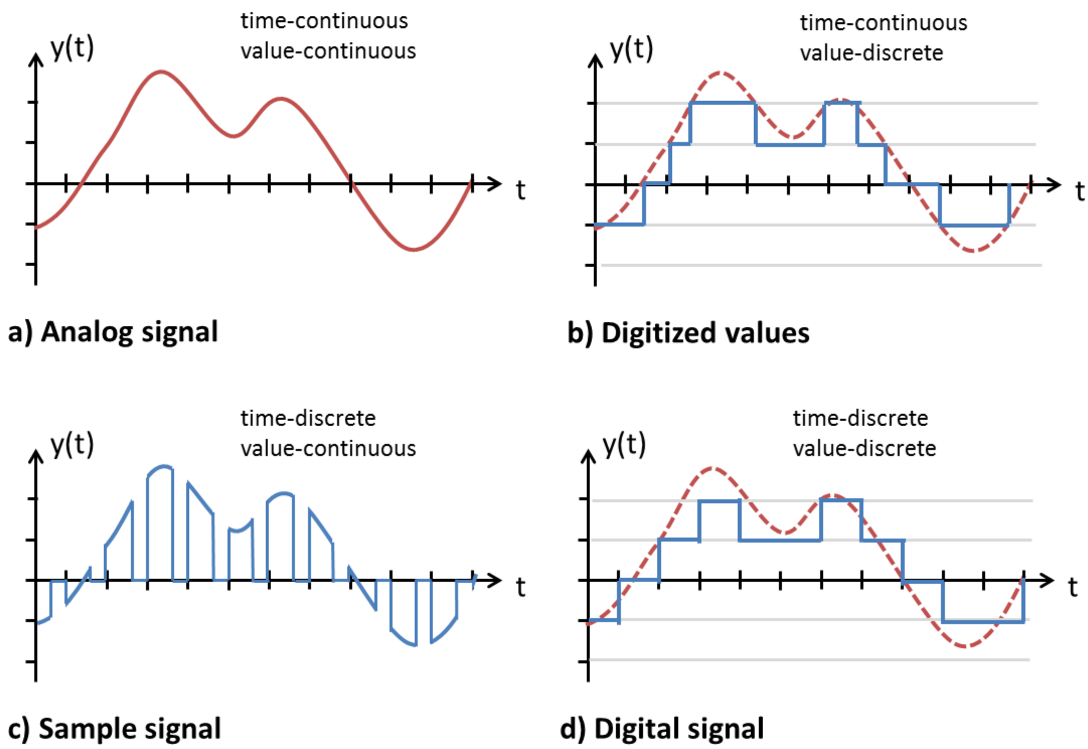


Figure 2.3: Visualization of quantization

of the signals is necessary. Otherwise two signals received at the same time in the information processing may refer to different instances of time.

2.1.2 Information transmission

The sender-receiver model, also known as Shannon Weaver model, describes communication as transmission of a message from one entity to another. The message is encoded and transferred as a signal via an information channel. Successful communication means that the receiver gets the same message the sender has sent. Thus, sender and receiver need to use the same codification, so that the decoded message is the same as the original one. The encoded message also can be altered by noise, so this needs to be detected and prevented. The original model of Shannon [26] is depicted in figure 2.4. The transfer of medical data is regulated by different standards. IEEE-11073 [27] is the technical standard that defines connectivity profiles for all different kinds of medical devices. Every device that measures vital data of a patient, that refers to this standard, describes in the data how the parameter was measured and when. With this knowledge the data of different devices become comparable and processable. The IEEE standard is incorporated in the British Standard BS11073. Another popular standard for medical data transmission is Health Level 7 (HL7), in particular version 3, that is supported by most systems that transfer, receive or process medical data. It uses a kind of comma separated values (CSV)

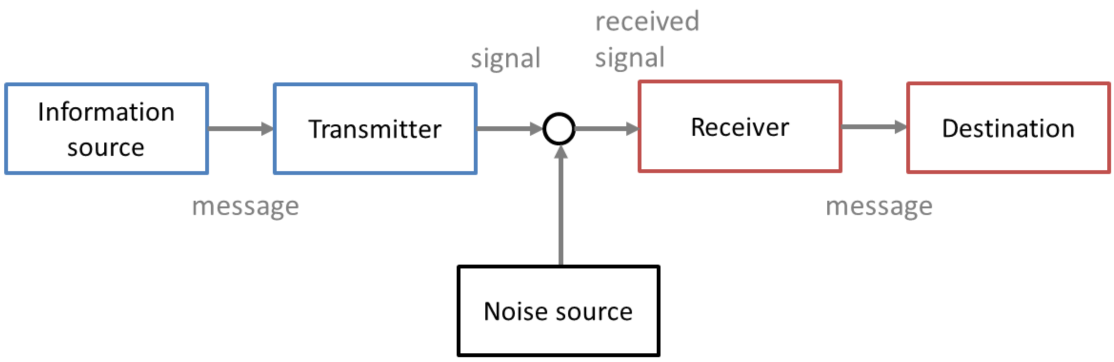


Figure 2.4: Schema for information transmission [26]

pattern to store the data. This allows a more efficient data transfer than Extensible Markup Language (XML). This is why it is interesting for low-power devices or battery powered equipment. Additionally, there is the Continua Health Alliance, that tries to spread the use of IEEE11073 via HL7v3 as a standard for communication between medical devices and other systems. They also create device design guidelines and certify systems against it [28].

2.1.3 Networks

Based on the general model of data transmission (see section 2.1.2), a multitude of questions need to be solved in order to receive an appropriate network connection. First, the information channel can consist of different physical media like copper cables or air (for radio transmission). Second, following the definitions in the last section, we also distinguish between analog transmission and digital transmission. Third, both partners need to agree upon several things: They need to negotiate who is sender and who is receiver in a bidirectional connection, which code they use, how much information they can send and so forth. Even more complicated, the Internet is a network of networks with a multitude of communication partners, different structures and transmission media.

To decrease complexity, most networks are organized in layers. Every layer provides specific services to the layer above, but hides details, so that the highest layer can focus on the message content. In order to explain some basic concepts, which characterize connection quality, we use a simplified model depicted in figure 2.5 for further reading see [29] or [30]. It is important to understand that the Internet is based on packet switching. Messages are fragmented in packets of the same size and sent individually. In our example in figure 2.5, a server is located in central Europe and has a message. Signals travel with limited speed, so that the packets have a delay between the sender in Europe and the receiver in China. As the packets are sent individually, they can take different paths and have different delays. The variation of the packet arrival times is called jitter. Packets may arrive in a different order or may not arrive at all. This is called packet loss and visualized with a missing

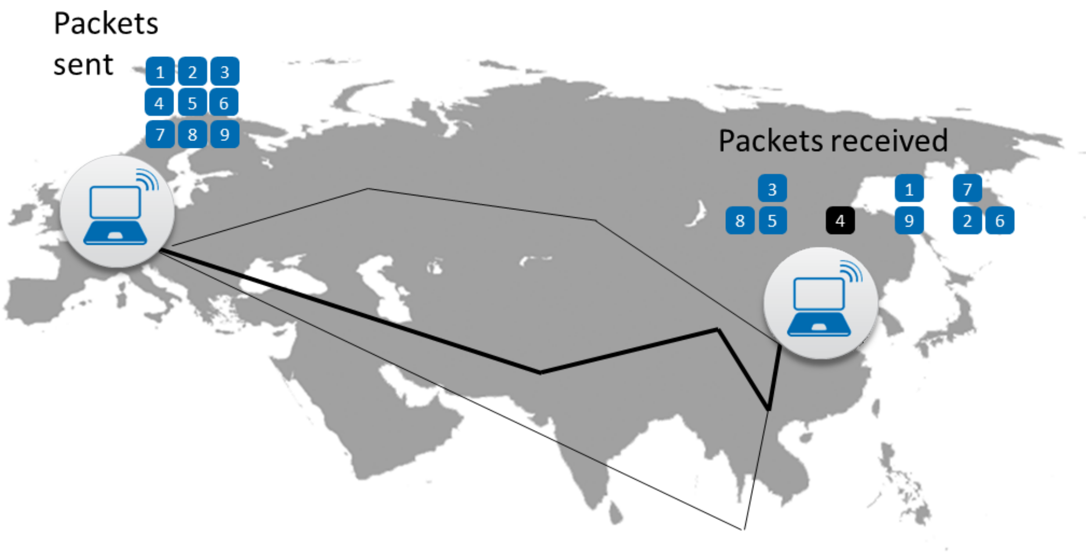


Figure 2.5: Schematic visualization of packet switching: A message is sent from Europe to China in packets, which will arrive on different transmission paths, in a different order, in different time or not at all (visualized in packet 4)

package (packet 4).

The last network characterization covered in this brief survey is the amount of data, which can be transferred, the throughput. There is a theoretical limit to the maximum rate at which data can be transferred over a communication channel of a specified bandwidth in the presence of noise (channel capacity) [26]. The term bandwidth describes the range of frequencies that make up a signal [30] and is used for characterization. But the amount of user data or payload is further shortened dependent on the used codification (overhead).

2.1.3.1 Security

Nowadays securing digital communication has a high significance, especially when personal data is transmitted. For that reason standards were developed, refined and revised to fulfill the current demands for secure data transfer. The most common security standard for data transmission over the Internet is the Transport Layer Security (TLS) standard, the successor of Secure Sockets Layer (SSL). It provides state of the art security encryption and is widely distributed. Nearly all of the used encryption algorithms are available as hardware chips or integrated in modern devices, like smartphones. That makes the development and usage of systems with secured communication rather easy.

2.1.3.2 User Datagram Protocol (UDP) hole punching

When systems are connected via communication links that are not located in the same network, the communication route is mostly unknown. Especially when the communication is realized over the Internet, there are routers in the communication route that do Network Address Translation (NAT) for the network behind them. This means that two devices cannot communicate directly if they are in different networks, that have at least one NAT router between them. To establish a communication between these devices one can use a method called UDP hole punching [31]. Usually a third device, like a public reachable server, is used to communicate with both devices in order to find a possible way for direct communication. If that is not possible, the server can be used as a relay for the complete communication.

2.1.4 Communication links

In telemedicine systems, different types of communication links are used. To achieve the requirements for the communication links the following characteristics need to be analyzed

- Distance between communication units
- Energy consumption of communication units
- Data transmission rate of communication links.

Figure 2.6 shows a comparison of different communication types in a coordinate system *mobility / range* over *data transmission rate*. This shows, that all communication types offer different data rates and different mobility characteristics. In general, communication types with high mobility offer lower data rates. Furthermore, communication types with a higher mobility have a higher energy consumption which is a critical aspect for sensors caused by shortened lifespan due to the limited battery. For this reason a combination of short range communication and long range communication is used.

2.1.4.1 Wide area networks for long range communication

To connect the end users like patients and doctors to the telemedical infrastructure long range communication links have to be established over wide area network (WAN)s. According to local conditions, different ways for long range communication can be used. Many households, office buildings and hospitals provide an environment with at least a digital subscriber line (DSL) connection which can be used to transmit data with high bit rates. Mobile devices like smartphones can access the DSL by using a WiFi connection. For mobile applications and households without a capable environment a communication link via universal mobile telecommunication systems (UMTS) can be established. UMTS provides a high mobility with the disadvantage of reduced data transmission rates (see figure 2.6). A characterization of UMTS links can be found in [32][33]. Due to new technologies like high speed

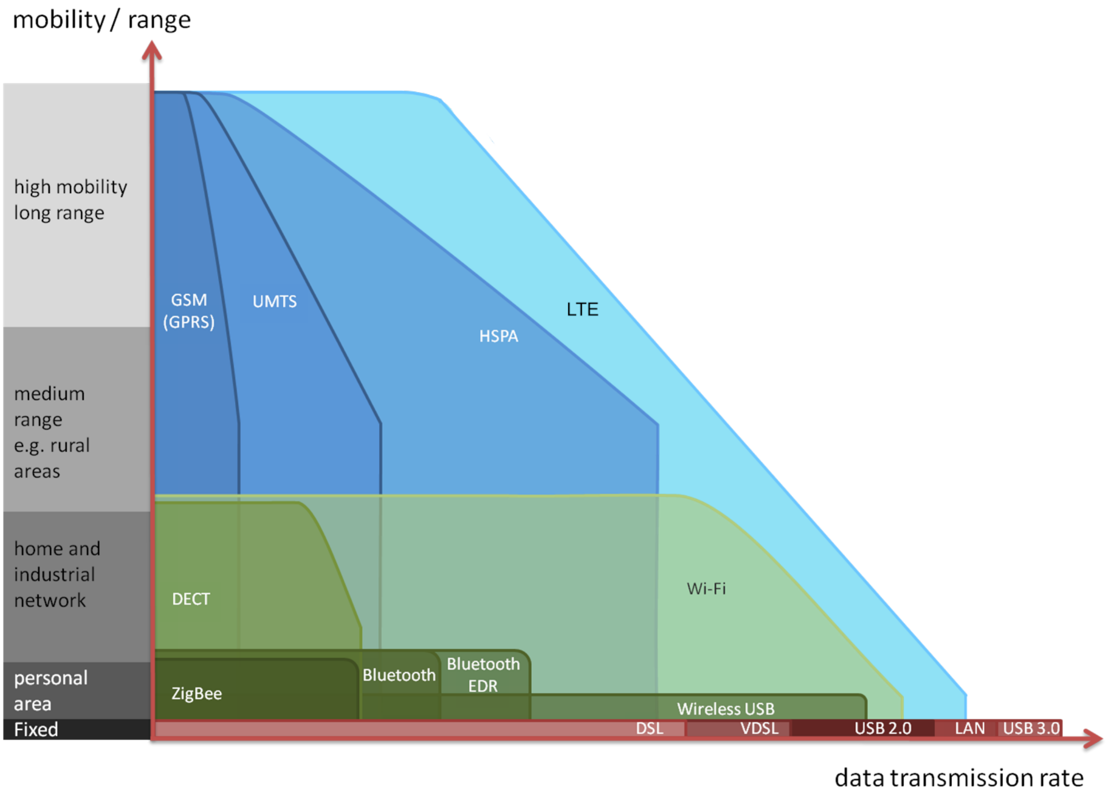


Figure 2.6: Comparison of the data rates and mobility for different communication ways

downlink packet access (HSDPA) or long term evolution (LTE) the UMTS link bandwidth and quality is a good fallback if no DSL is available. Depending on the amount of collected data and the available communication links the data acquisition has to decide which information has to be transmitted. If not enough bandwidth is available, the device has to preprocess the data and transmit the essential information. If a higher bandwidth is available later, the device can retry the transmission of the data.

2.1.4.2 Personal Area Network technologies for short range communication

For the communication between the sensors and the collection of the sensor data by a data acquisition unit short range communication links has to be established using personal area network (PAN)s. PAN technologies offer the following characteristics:

- higher data rates
- lower power consumption
- small operating distance
- adaptable and specialized communication protocols

Bluetooth is an established technology for PAN and is supported by almost every mobile device. The Bluetooth health device profile (HDP) is a protocol that has been developed for transmitting medical data over Bluetooth. The standardization provides a defined data structure for interchanging medical data between sensors that are defined in IEEE 11073 [27] and other devices that implements the HDP. Relying on standardizations like Bluetooth HDP and IEEE 10073 enables modular data acquisition that is easy to extend. A comparison between Bluetooth HDP and the well known serial port profile (SPP)[34] shows that the transmission energy of the two profiles is similar, however HDP has the advantage of plug-and-play interoperability.

2.1.4.3 Round trip time, jitter and packet loss rate

The round trip time (RTT) is the time a packet needs to travel from a source (client) to a target (server) and backwards [35]. Figure 2.7 shows the different time components that add up to the RTT of a packet. T_P is the time that is needed to transmit all the bits of a packet. This time mainly depends on the packet size (S) and the bandwidth (R) of the link, i.e. $T_P = \frac{S}{R}$. T_T is the time that is needed to receive the first bit of the packet by the target, after it was send by the source. T_T mainly depends on the distance between source and target and the speed of the signal propagation. The transmission time of a packet $T = T_P + T_T$ is the time until the whole packet is received by the target. Analog to this $T' = T'_P + T'_T$ is the time the packet needs to be sent back. T_C is the time the server needs to compute the packet until sending it back. Given this the round trip time of a packet is $RTT = T + T_C + T'$. With n as the number of test runs and RTT_i as the measured

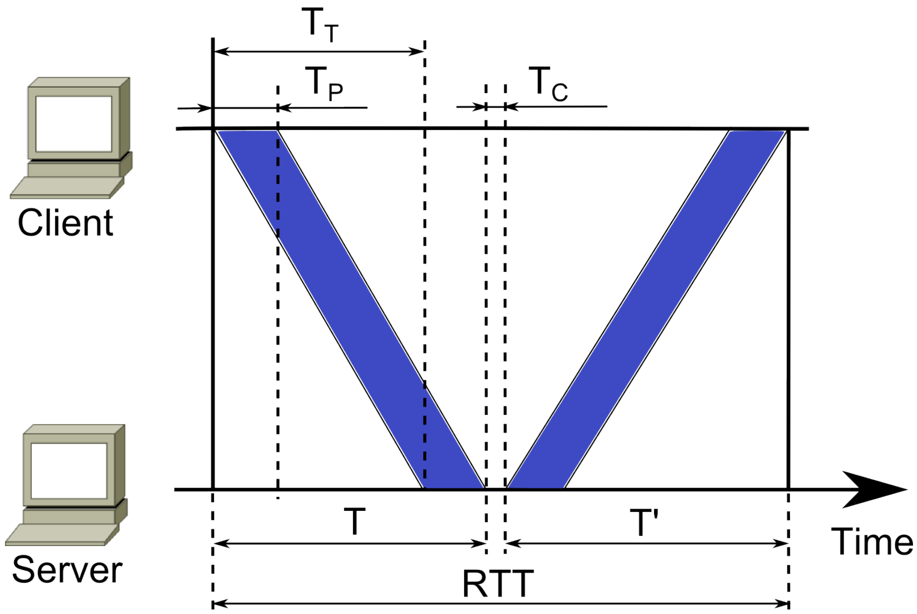


Figure 2.7: Round Trip Time of a UDP packet. The packet is sent from the client to the server and afterwards replied from the server to the client.

round trip time for the test run i the mean RTT for one setup with a specific packet size is calculated by

$$RTT = \frac{\sum_{i=0}^{n-1} RTT_i}{n}.$$

Furthermore the jitter as the variance of the round trip time is calculated by

$$Jitter = \frac{\sum_{i=0}^{n-1} (RTT_i - RTT)^2}{n}.$$

When l is the number of test runs with packet loss, then packet loss rate (PLR) is defined by

$$PLR = \frac{l}{n}.$$

2.2 Medical treatment

Medical treatment of a dramatically growing number of people in the industrial countries is a big challenge for healthcare systems. Constantly rising costs and a lack of qualified doctors and nurses are only two of them. In the last years there have been many activities using modern communication systems and sensors for monitoring patients at home, see [36]. It has been predicted, that home monitoring of people suffering from heart insufficiency can safe up to 6.4 billion dollars by reducing the number of emergency hospital visits, see [37]. A realtime capable patient monitoring system (ECG) was already realized and published more than ten years ago [36]. The project used Bluetooth for communication between a ECG-Sensor and a mobile phone, used as Global System for Mobile Communications (GSM)/general packet radio service (GPRS) modem. Despite the cost reduction, patient monitoring and treatment at home has positive psychological and physical effects on the patient which can be labeled as effects of ambient assisted living (AAL). He does not need to go to hospital as frequently as before, at the same time, his medical status can be observed more frequently by doctors as it is transferred in short intervals, depending on the measurement and treatment. In order to build a system that supports the treatment of different diseases we first have to get an understanding of the progress and characteristics of the diseases. This section gives a basic overview for the diseases we want to address with our use cases: COPD, dialysis and intensive care. The latter is not a specific disease but has its own requirements to the system that have to be regarded.

2.2.1 COPD - Chronic obstructive pulmonary disease

COPD is a progressive disease of the lung and a growing problem [38]. The Global Burden of Disease identified COPD as the fourth leading death worldwide in 2004. COPD is projected to be the third leading death worldwide in 2030 [39].

COPD is defined by the Global Initiative for Chronic Obstructive Lung Disease (GOLD) standard as follows: *"COPD is a common, preventable and treatable disease that is characterized by persistent respiratory symptoms and airflow limitation that is due to airway and/or alveolar abnormalities usually caused by significant exposure to noxious particles or gases."* [40, p. 6]

The most common symptoms of COPD are: Breathlessness, Coughing, Sputum and Wheezing.

Smokers have a high risk for getting COPD. The illness is progressive which means that the lung capacity decreases by time. From time to time an acute worsening of the lung capacity can happen. This is called an exacerbation. Usually, an exacerbation accompany a breakdown of the patient and therefore a longer stay at the hospital, mostly in intensive care.

COPD is divided in four degrees of severity which is related to the amount of lung capacity left to the patient and the score of the COPD Assessment Test (CAT) [41]. CAT is a questionnaire designed to measure the impact of the illness to the daily life of the patient. The higher the degree of severity of a patient, the more exacerbations happen. Patients with a higher degree of COPD sometimes have to be mechanically ventilated. The loss of lung capacity often results in a reduced mobility of the patients that leads to decreasing social interactions.

COPD was chosen to be one sample application for our system due to the high and rising amount of patients and their implications on the health system. A remote supervision of these patients promises a reduction of hospitalization and therefore a reduction of costs [42, 43]. The physicians expect to find parameters that, when monitored over larger periods, can predict exacerbations and allow to take preventive actions. That would result in slowing down the degradation of lung capacity and keep the patient mobile and social integrated.

2.2.2 Dialysis

Patients with renal failure need to compensate basic renal functions by advanced technical and medical means. Being one of the most complex organs, the kidney performs many vital tasks. It regulates the amounts of water and minerals like sodium, potassium and chloride in the body. A further major function is the excretion of acidic and toxic substances, despite of its functions inside the body's endocrine system. When the patient suffers from an entire failure of the kidney it is called end stage renal disease (ESRD).

The main effects of ESRD are:

- No excrementation of urine, therefore water management disorder and water deposition inside body.
- No excrementation of urea and risk of intoxication by potassium and other substances.
- Anemia in cause of insufficient production of Erythropoetin (EPO) hormone.

These processes, which cannot be performed by the kidney anymore, have then to be done by machines. This treatment is called dialysis and is commonly known as blood purification. There are two different methods for dialysis that are widely spread: Hemodialysis (HD) and peritoneal dialysis (PD). At the HD the blood is filtered extra-corporal. Water is extracted by an additional pressure gradient across the dialysator membrane, resulting in water diffusion though the membrane. PD uses the peritoneum to filter the blood inside the patients body. During PD, water extraction is realized by sugar molecules in the dialysis liquid. As the concentration of sugar is higher in the dialysis liquid than in the body, water is flowing through the selectively-permeable peritoneum by an osmotic process. A schematic plot of how the metabolic end products are extracted from the body in both methods is given in figure 2.8. Every single treatment follows a so called dialysis regime that is adapted to the current condition of the patient. The main parameters that can be changed for the dialysis regime are:

- Duration of the treatment,
- Ultra-filtration rate, that is the amount of water that is extracted in a defined time, and
- Composition of the chemicals in the dialysate to filter the right amount of substances out of the blood.

They all influence the quality of the treatment and the wellbeing of the patient. An extended treatment duration for example allows a lower ultra-filtration rate that

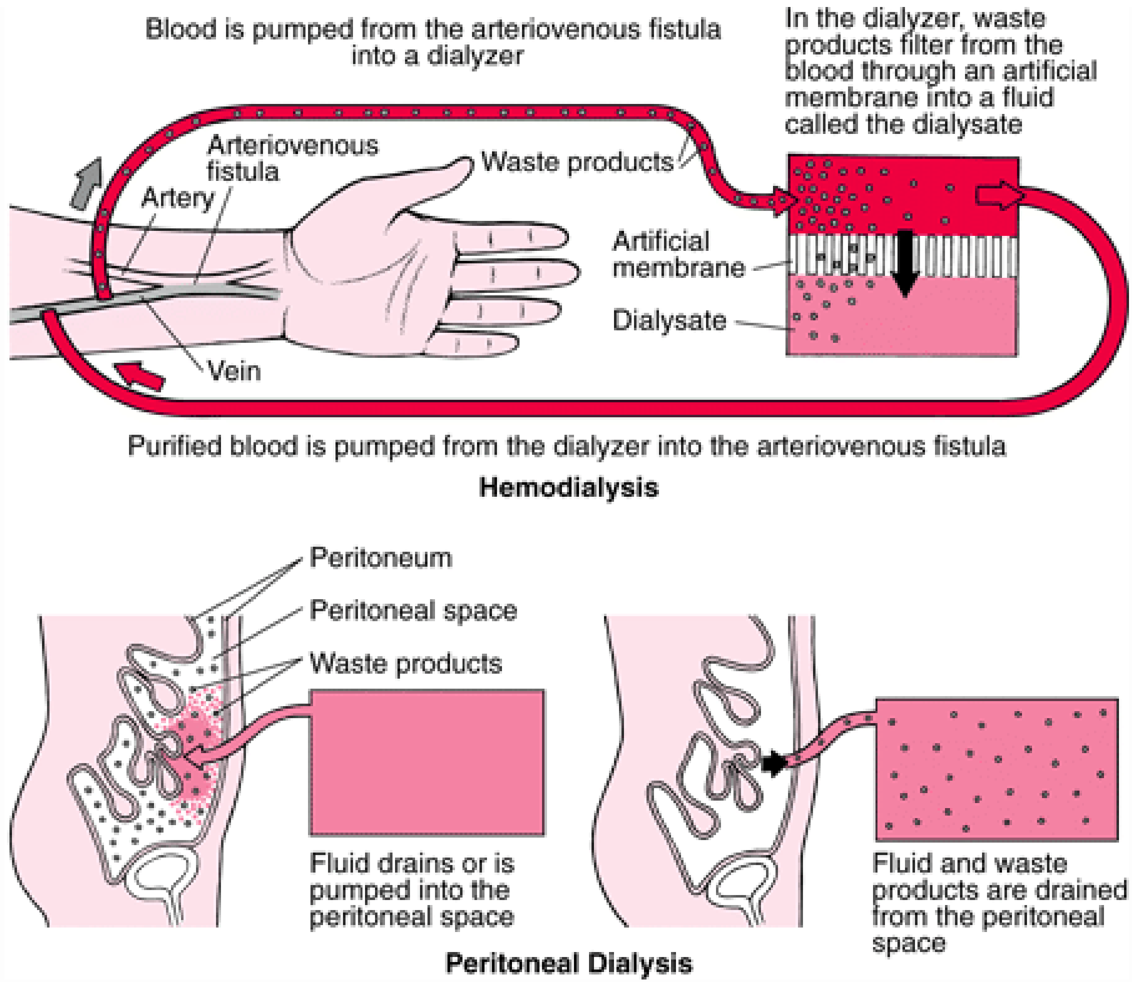


Figure 2.8: Common dialysis techniques. HD and PD. Source:[44]

results in lower strain for the cardiovascular system. The patient can therefore regenerate faster from the treatment. The overall quality of the treatment is measured by the Kt/V value, where K stands for the urea clearance, t is the treatment duration in minutes and V the amount of water in the patients body [45].

Dialysis treatment in Germany Germany was offering dialysis treatments to about 63.000 people in 2005 [46]. Among these, 75 percent are ambulatory treated in dialysis centers, meaning three visits per week, staying for three to five hours closely connected to Hemodialysis machines, extracting acidic substances and about three to seven liters of water out of the patients body. The water was accumulated within the days since the last treatment, due to the total loss of renal functions without any urine production at all. PD is not as commonly used (about 5 percent in Germany [46]) as the HD although it allows patients to treat themselves at home, at work or during voyages. Even though it is possible to do HD at home this is only performed by 0.8% of the patients [46]. Figure 2.9 shows dialysis machines for performing HD (upper one) or PD (lower one), manufactured by Fresenius Medical Care [47]. The dialysis treatment is very expensive. An average treatment for a dialysis patient costs about 40.000 Euros per year while the transportation costs for the patient is about 30 percent of this value [48]. The patients have to be transported to and from the dialysis centers due to the fact that the treatment is very stressful to the cardiovascular system. After a treatment the patients are unable to drive or work for the rest of the day.

Despite the dialysis treatment can easily be performed in a dialysis center in Germany, we decided that home dialysis is an excellent application for telemedical remote assistance. Since the number of dialysis patients is continuously growing, the capacity of most dialysis centers is on its limit. In addition there is a lack of qualified personnel for supervising each treatment of the patients. Home dialysis is an option, that is offered to all appropriate patients due to the reduction of costs and workload this alternative induces. In various interviews we identified the main reason for patients to decline a home dialysis: The patients have a great fear of being less supervised and alone in some cases of emergency. A telemedical system can bridge the spatial distance between the doctor and the patient facilitate an equal supervision at home.

2.2.3 Intensive care

At the intensive care every second counts. Due to the decreasing amount of physicists in rural areas, there is a lack of competence which leads to increasing reaction times. This creates additional risks for the patients' health and lives. The information exchange between hospitals with expertise in intensive care and their peripheral hospitals is realized via telephone support and questionnaires that are sent by fax. The experts have only a short amount of time to decide if the patient can be treated at the peripheral hospital with some remote support of the expert or if the patient has to be transferred to the better equipped hospital. The transfer of the patients is

(a) HD Machine 5008 by Fresenius Medical Care [47]

(b) PD Cycler by Fresenius Medical Care [47]

Figure 2.9: Dialysis machines by Fresenius Medical Care [47]

extremely costly because the patients are very unstable. Transferring the patient is done via specially equipped ambulances or helicopter. In extreme cases of emergency the experts travel to the patient by helicopter to start the extended treatment right at the remote hospital. Figure 2.10 shows the current information exchange between the two hospitals and the work-flow of the remote support scenario.

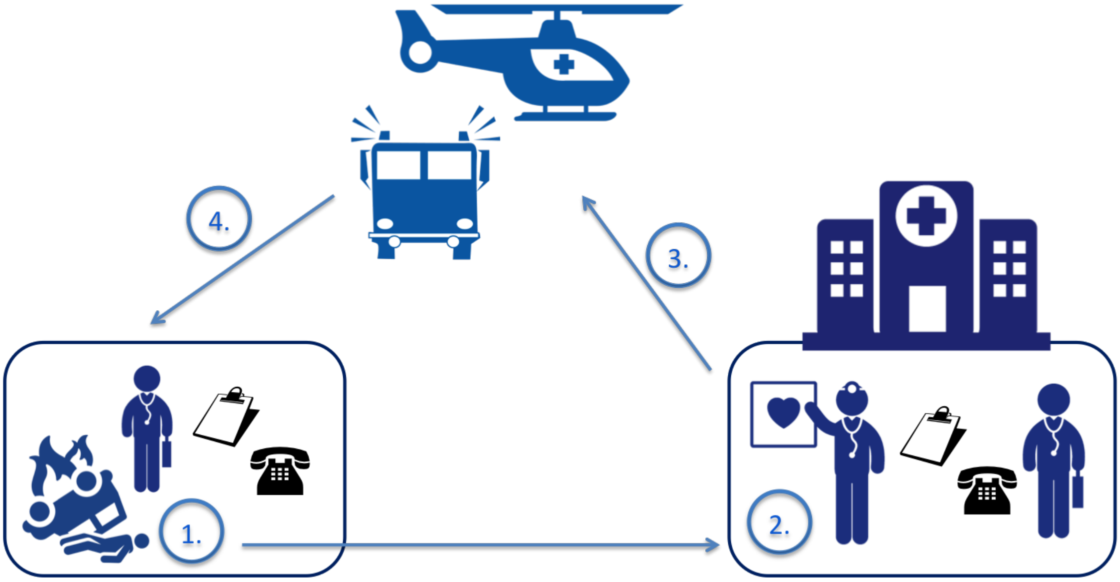


Figure 2.10: Current work-flow and information exchange over telephone and fax at an intensive care support scenario

2.2.4 The user experience process

A high quality user experience can be ensured by applying a consequent process as described in [49]. The described "UX cycle" (see figure 2.11) mainly consists of the steps analysis, design, prototype and evaluation, while the repeating of one step or jumping back to the last step is encouraged. In figure 2.12 the design process is visualized with different important steps, although there is the possibility for an iterative procedure as described in the "UX cycle". The first step is contextual inquiry, a early system activity "to gather detailed descriptions of customer or user work practice for the purpose of understanding work activities and underlying rationale. [...] Contextual inquiry includes both interviews of customers and users and observations of work practice occurring in its real-world context." ([49, p. 89]). It is followed by contextual analysis, "a systematic analysis - identification, sorting, organization, interpretation, consolidation, and communication - of the contextual user work activity data gathered in contextual inquiry [...]" ([49, p. 129]). In figure 2.12, the raw data from contextual inquiry is interpreted in work activity notes. Those are "used to document a single point about a single concept, topic, or issue

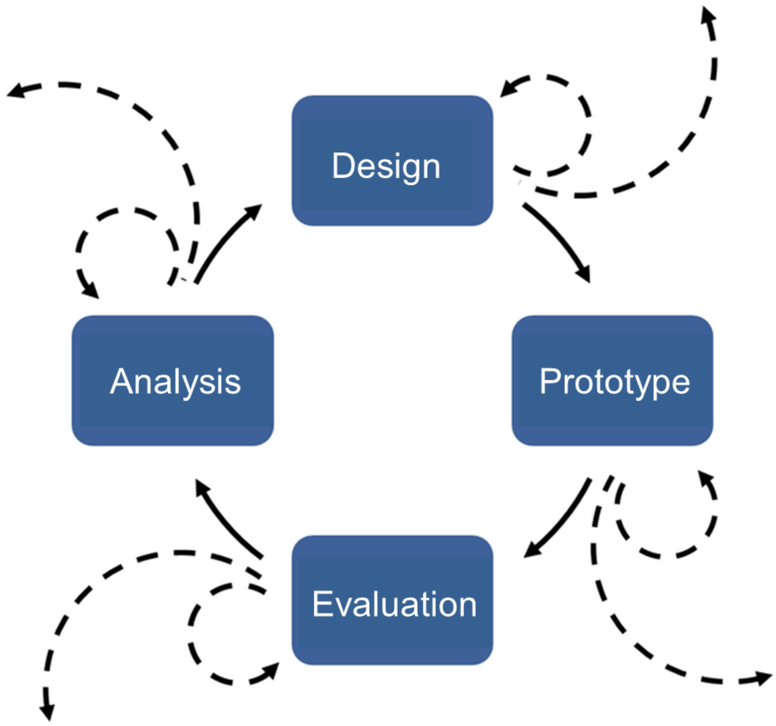


Figure 2.11: The user experience development cycle (following [49])

as synthesized from the raw contextual data." ([49, p. 131]). Afterwards, they are clustered in a so-called work activity affinity diagram (WAAD) and are used to extract software requirements and design-informing models. The latter are "design-oriented constructs, such as task descriptions or user personas, that turn raw data into actionable items as design ideas, as elements to consider or take into account in the design." ([49, p. 183]). There are different kinds of design informing models like flow models (overview of work process), user models (different work roles or personas) or social models (the relations between different work roles). Depending on the task and complexity of the work domain, different models can be chosen and should be generated in team work and iterated with domain experts, if possible (for a detailed description see [49]). The most important role of the models and the detailed inquiry is to depict the actual state of the work environment and to reason about an envisioned future state which shall be reached with the new product. This is also called the "design gap" [49] which can be bridged with the methods described above.

The design process can be categorized in the steps "Ideation and sketching", "Conceptual design", "Intermediate design", "Detailed design" and "Design refinement" [49]. Some steps overlap in practice, while different mediums like sketches, storyboards, illustrated scenarios, wireframes and visual comps are used. They are evaluated in the team at first, but later also with end users.

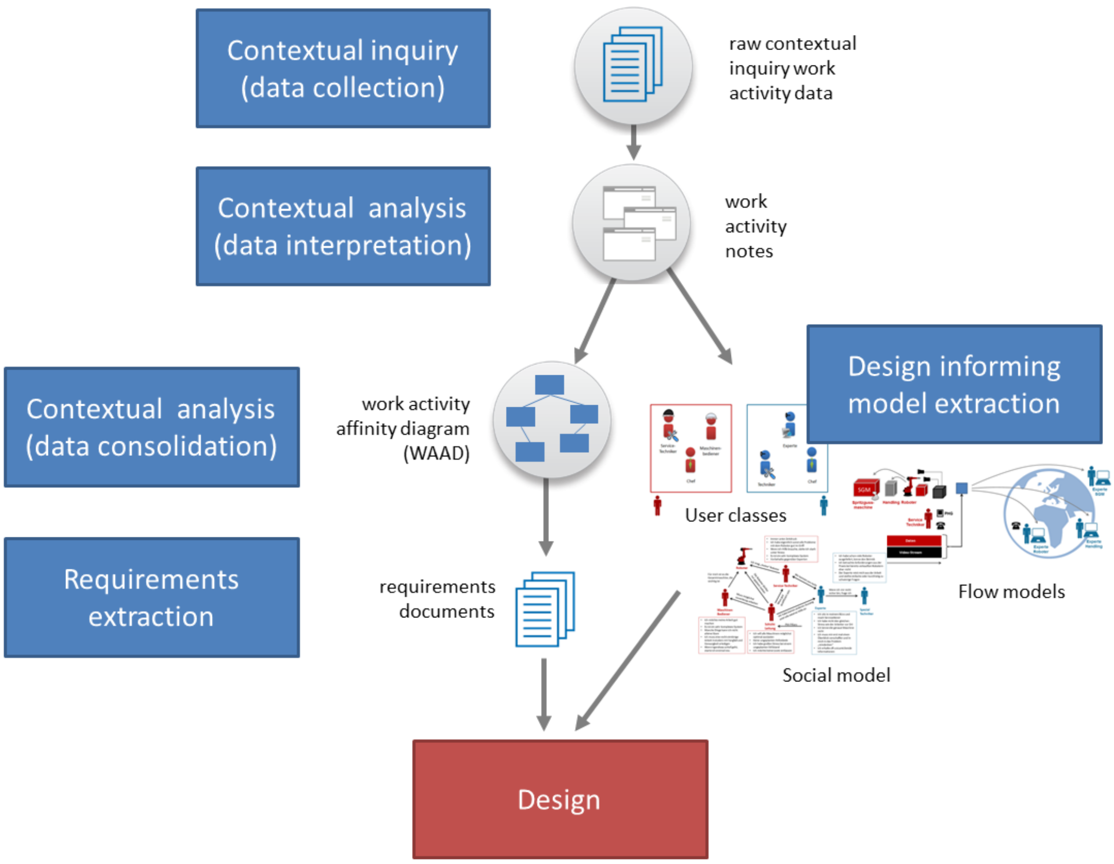


Figure 2.12: The user experience development process (according to [49])

2.3 Big data and data mining

The term "Big Data" has been mentioned a lot recently, some even call it the "oil of the 21st century". McKinsey & Company has nominated it as "the next frontier for innovation, competition and productivity" [50]. In the year 2012 worldwide 4.6 billion euros have been invested in Big Data related projects and services [51].

Although different definitions are still used, the scientific literature agrees, that the distinctive feature of Big Data and its challenges and benefits evolve from the increasing amount, velocity and variety of data, as the META Analyst Doug Laney has described in 2001 [52]. The term data mining has become a synonym for "Knowledge Discovery in Databases". According to Fayyad et al. [53] this description emphasizes the process of data analysis rather than the use of tangible methods for data analysis. As depicted in figure 2.13 the process of knowledge discovery is mostly done by integrating the data of various data sources into a data storage, which is often represented by a database. After preprocessing the data, data mining is used to extract patterns or correlations which are transformed into knowledge. The data mining process is meant as a process to find correlations or patterns in data to provide the data analyst a useful result [54]. The results are then used to predict similar future events. Solving data mining problems makes use of different approaches from computer science, like machine learning or data visualization, and from statistics, such as clustering, regression tests or classification techniques [55]. The difficulty is to combine these methods in a efficient manner to solve a given data mining problem. If the expected result is categorical or numerical, the predictive method can further be classified into classification and regression tasks.

Data mining tasks are often classified into tasks of description and prediction. Description tasks aim to classify data according to patterns or categories in order to structure it for humans, while prediction is used to analyze the data in order to find a model to generate forecasts of specific events. To predict these events the data needs to contain parameters, that represent the occurrence of such events.

From a scientific point of view, Big Data is no new hype, but a new dimension in the cooperation of different scientific domains. In the domain of medicine, data mining promises the gain of new knowledge about diseases and unknown correlations between parameters that help for a better understanding of the progress of diseases or lead to better treatments.

2.3.1 Data

Data mining works on a data set of examples which are often called instances. This can be structured or unstructured data. In the first case, we can think of it as structured in a table. In the latter, we need to perform some search actions to transform it in a structured form. Each instance consists of numerous variables, which are called attributes.

If there is a specially designated attribute we can think about it as a column header. Data of this kind is called labeled data and algorithms dealing with such

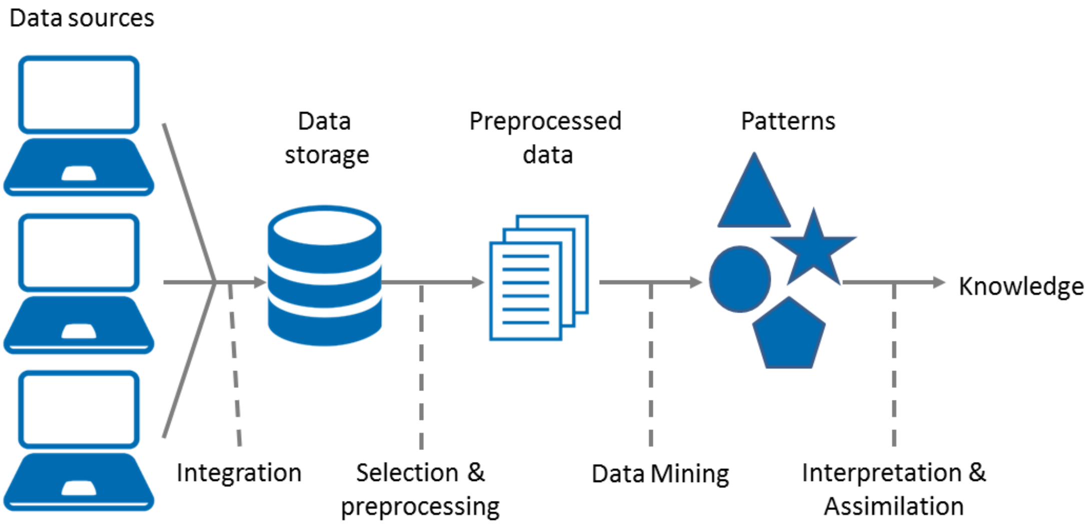


Figure 2.13: Knowledge discovery scheme from [56]

kind of data are called supervised learning [57]. Data without any specially designated attributed is called unlabeled data and the associated algorithms are called unsupervised learning [58].

Normally, a data set is partitioned into training data and validation data. The goal is to detect patterns in the training data. The associated algorithms are then used on the validation data to "sort" them according to the patterns. This task is different for the different types of labeled data.

It is further divided on the attribute type: It can be categorical, that means it describes a category like "good" or "house". Then the task of dividing the data with respect to the attributes is called classification. Otherwise, the attributes can be numerical. Then the task is called regression (cf. [56]).

Generally the recorded data needs to be verified (cf. [59]). Through different circumstances the data can be altered, so that a result is faulty or the plotted data is visualized wrong. Some errors occur through programming errors or hardware errors in the data acquisition. But of course the values may also have been generated by the observed object in that way, which tends to be the most interesting part of the data (cf. [60], [61]).

It must be clarified, if the data shall be visualized only or also explored. Users often see pattern during data exploration. If those patterns are recognized correctly can only be estimated with one or several confirmation steps afterwards (cf. [62]).

2.3.2 Data mining methods

Statistical analysis (see figure 2.14) With statistical analysis methods, like linear and non-linear regression, a prediction for data streams can be derived. In many situations, a critical state cannot be detected out of one parameter, but out of the combination of several measurements. Thus, mathematical procedures are applied to enable a combined consideration of the data.

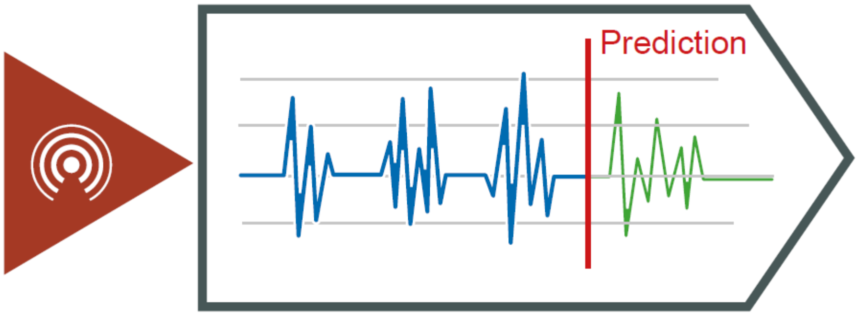


Figure 2.14: Statistical regression for prediction of a future state

Semantic rules (see figure 2.15) Often experts are able to describe connections between signals, states and events in the form of rules. If the desired behavior of several components is described with semantic, domain specific rules, a deviation in current data can be detected. It is important that experts define and use the rules

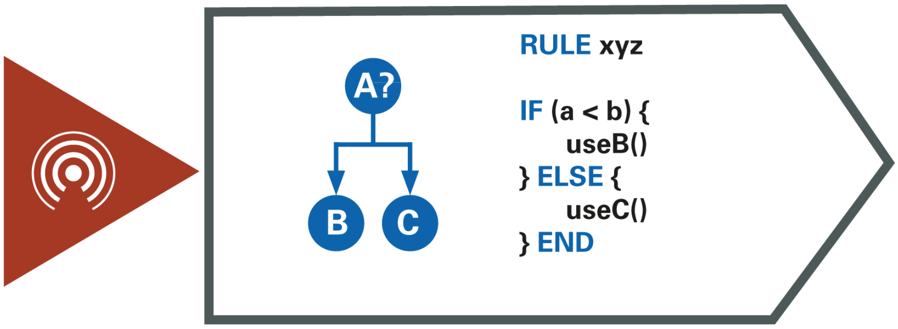


Figure 2.15: Rule-based fault detection

as simply as possible. The use of a domain specific language is necessary to explain abstract concepts and interrelations.

Use of reference cases (see figure 2.16) Next to rule based connections there is also a huge treasure trove of experience in form of reference cases. Data of the past of a patient or patients with similar diseases describe the expected state of a healthy person and give indications on the factors that led to a disease or worsening of the patients condition. With the help of case-based reasoning (CBR) a "signature" of the current state can be derived. This can be compared to the huge amount of reference cases in the historic data as shown in figure 2.16. Based on the classification of past data critical situations and symptoms can be estimated.

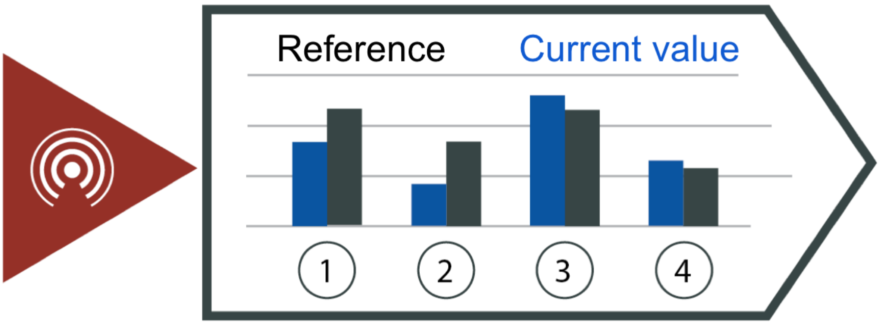


Figure 2.16: Diagnosis with reference cases

Decision trees (see figure 2.17) For the classification of data, decision trees can be designed, which decide on single attributes of a data set, in which category it needs to be sorted. Additionally nearest neighbor methods can be used to determine as much mutuality to other data sets as possible [56].

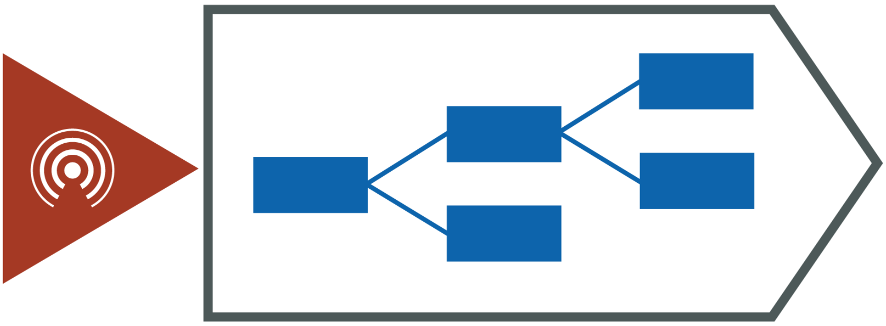


Figure 2.17: Use of decision trees

The decision tree algorithm creates a graph, that is growing downwards from the root at its top. The algorithm is given a set of example data and tries to create a model for prediction of an attribute in the data that is called target attribute or label. Each leaf of the tree represents a value of the target attribute. Every inner node in the tree represents an attribute in the training data. The edges, that are linking the nodes, generate a path from the root to a leaf that represents the conditions for the classification of the data (cf. [63, p.52ff]).

The tree graph is generated by recursively going through the data and splitting it on the values of the attributes. In each recursion step, the algorithm selects an attribute to split the data on. The selection of the attribute depends on the calculated entropy, which quantifies the information content of an attribute. The entropy is calculated as follows: $\sum_{i=1}^{n} -p_i log_2 p_i$ where n is the amount of attributes and p_i the probability value of the attribute i. Attributes with a minimal entropy are selected for a split because they provide the highest information gain. An entropy of 0 would result in a leaf. The algorithm stops when all examples of the training data are classified. There are other conditions for stopping the recursive processing that can be adjusted to achieve a resulting tree that is not over- or under-fitted: a minimum information gain threshold for attributes, a maximal depth for the tree and a threshold for examples in a subtree. The tree can also be pruned during the creation of the tree (pre-pruning) or after the tree is completed (post-pruning). Pruning is the process of removing leafs or subtrees that do not contribute to the distinction of the different classifications. The pruning process can also be adjusted by setting thresholds.

Combination of different methods (see figure 2.18) For recognizing complex system connections or detect health/disease indications, the methods described in the previous sections need to be combined. Each of the methods has specific advantages and disadvantages why an integration and interconnection is necessary and leads to better and more stable results.

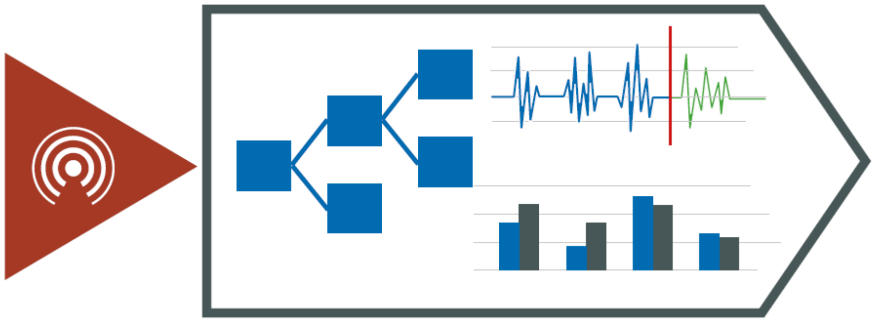


Figure 2.18: Integration of different methods

2.3.3 Data mining for medical applications

The process of filtering and analyzing medical data is a research topic quite a long time. Prominent and latest examples for data mining in medical application are drug therapy [64] or cancer research [65]. The range of medical applications that profit from data mining techniques is very broad [55]. But not only areas where there are obviously huge amounts of data to analyze, like in the genomic medicine [66][67], profit from data mining techniques. Nowadays, the amount of medical knowledge that is generated is much higher than a physician can learn, even if he or she would read publications all day long. Therefore we need the help of algorithms that condense the knowledge to fewer information that are relevant in the medical personnels current situation. The use of decision support systems, that base on data mining methods, could provide such a support for the medical staff. An efficient decision support system could alert the doctors if a patient is in need of an examination or even a critical intervention is needed [68].

2.3.4 Data mining for industry applications

There is an increasing interest on data mining approaches in the production industry [69]. But there are several reasons, why the development of data mining for the automation industry is approaching only slowly: On the one hand the majority of the scientists having knowledge in the industrial domain are inexperienced in data mining algorithms and data mining software. On the other hand data mining scientists lack the detailed knowledge of complex plants and production processes. The few experts with knowledge of both domains often are not allowed to access the sensible and protected factory data [69].

But especially the use of sensor information for process control has a huge potential for optimization [70]. The semantic analysis of the data of several plants is expected to provide more information than the analysis of only one plant [69]. So a huge room for maneuver for optimization is expected on a large scale [71].

Experiences from other application domains [72] show, that on a complete system data mining techniques can help to detect pattern which lead to abrasion and material fatigue. So the lifespan of the different elements can be estimated for an optimal predictive maintenance. With the high product quantity in the manufacturing trade, already small improvements have significant influence [73].

2.4 Summary

Telemedicine systems have to reproduce a lot of complex tasks and connect various users. In order to build a generic telemedicine system, different methods and techniques have to be combined to form a system, that supports all of its users and provides a value for all the stakeholders. Figure 2.19 summarizes all the building blocks for an intelligent and generic telemedicine system, that provides all needed modules from data acquisition to data transmission and communication to data analysis and visualization.

Figure 2.19: Building blocks for a generic telemedicine system

Chapter 3

State of the art

This chapter gives an overview to existing systems and techniques in the different fields. It describes the integration of this work in its scientific scope.

3.1 Telemedicine systems

The development of modern telecommunication technologies have created new opportunities and in the past years different telemedical systems were developed to support the treatment of specific diseases and patients. Most of them were developed to support the treatment of patients with chronic heart failures like the next examples show.

Due to the development of modern telecommunication technologies different systems offering telemedicine evolved over the past years [14]. The “Trans-European Network-Home-Care Management System” (TEN-HMS) study was the first international study, that verified advantages of using telemedical systems in complement to the normal treatment of patients with chronic heart failure [74, 75]. The structure of the telemonitoring system of this study is depicted in figure 3.1. In this study the patient’s weight, blood pressure, heart rate and heart rhythm were monitored twice daily resulting in a reduction of hospital readmissions and the days spend in hospital. Furthermore, an analysis of this project showed a reduction of costs, when complementing the normal treatment of patients with chronic heart failure with the tele-monitoring of the patients vital parameters [76]. Extending the results of the TEN-HMS an efficiency analysis was introduced based on the data provided by the telemedical project Zertiva® [76]. The analysis showed a reduction of costs, when complementing the normal treatment of patients with chronic heart failure with the tele-monitoring of the patient’s vital parameters. Table 3.1 shows the overall costs of the standard treatment in comparison with the telemedicine treatment of the project Zertiva®. In the “Telemedical Interventional Monitoring in Heart Failure” (TIM-HF) study of the research project “Partnership for the Heart” a remote telemedical management system was developed to monitor the vital parameters of patients with chronic heart failure and prove the facts provided by the TEN-HMS study [77, 78]. In this study the patient’s weight, blood pressure, oxygen saturation and electrocardiogram was monitored every morning. In addition the activity of the patient is recorded continuously with an activity sensor. The device, that was used

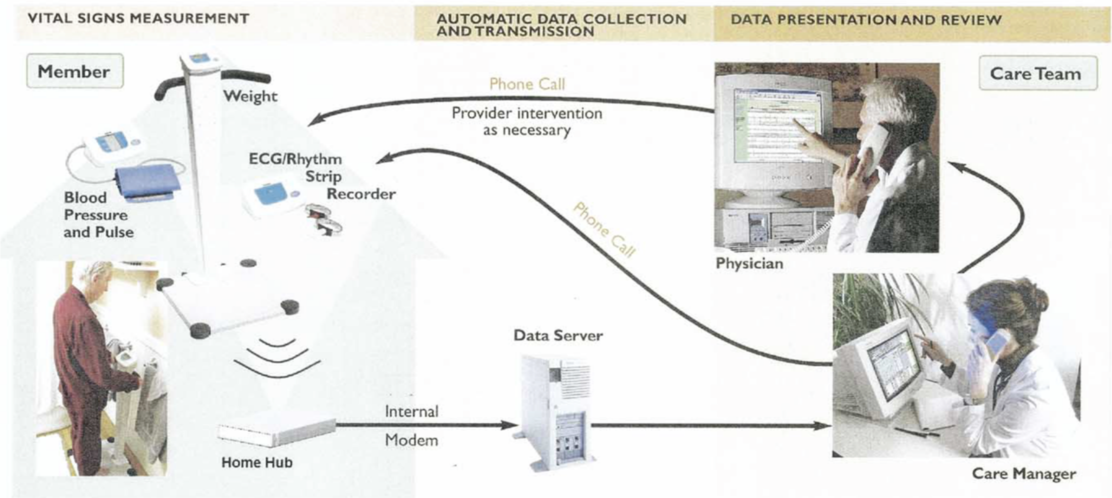


Figure 3.1: Diagrammatic representation of the telemonitoring system used in the TEN-HMS trial, taken from [75]

Table 3.1: Overall and effectivity adjusted costs, taken from [76]

Cohort	Overall costs (€)	Success rate (%)*	effectivity adjusted costs (€)
Standard	3.746	0.586	6.397
Telemedicine	2.292	0.748	3.065
* values from the evaluation of the Zertiva® telemedicine project			

to collect the measured data and perform the questionnaire, was called "Healthbuddy" and has been developed by Bosch in the research project. This study came to the conclusion that the use of remote telemedical management can improve the quality of life for the patients and especially unstable patients and their medical situation can benefit from it.

To support the treatment of patients with diabetes the telemedical care program "Diabetiva" was developed [79]. By regularly monitoring the patients blood sugar the patients quality of life and health status shall be improved.

Prominent examples of telemedicine systems, that could be established in the regular care are stroke networks. There are several networks like STENO [80], TEMPiS [81], TESS [82] or Transit-Stroke [83]. These networks were established to connect competence centers for treatment of stroke patients with smaller hospitals, that lack the expertise of treating strokes. The medical personnel can request help from the centers via video-conference and transfer of medical data. By now about 3000 tele-councils are held via the STENO network per year [84]. Another use case for this communication infrastructure is training of the medical personnel in the smaller hospitals and formation of interdisciplinary stroke units [85]. Besides the stroke networks, there are some other networks, that use telemedicine to provide similar support for other diseases like heart insufficiency.

3.2 Rule-based decision and filtering systems

The steady development of new telecommunication technologies over the past years leads to a growing amount of systems offering telemedicine [14]. Home monitoring systems as one kind of telemedicine offer remote supervision and support of patients in their usual environment of living. Studies showed that telemedical systems reduce the amount of treatment days in hospital. Therefore costs to the health care systems can be reduced while improving the quality of life for the patient [86, 87]. With nowadays capacities in telecommunication and data storage each telemedical system is able to handle a huge amount of patients. But this leads to a shortage of skilled medical personnel, that is able to handle the amounts of patients and provide a high quality treatment. In order to provide a good quality of medical supervision in a scalable telemedical system the workload of medical personnel needs to be reduced by intelligent data processing.

Medical decision support system (MDSS) are researched since the 90th [88, 89, 90]. While many of those use machine learning algorithms to create new knowledge, others rely on the knowledge that physicians formulate in rules [91]. These are limited to the knowledge they get from the experts. Most approaches were made to achieve a MDSS for creating automated diagnosis of diseases like a system that creates diagnoses based upon a rule set [92]. These systems are not very practical due to legal problems in many countries. The responsibility for a diagnosis has to be with a physician. Therefore an automatic diagnosis system will not be accepted. The systems became a knowledge database to support the physicians and research on this topic decreased. Some new systems are developed to assist in staff workload and effective communication [93].

Typically telemedical systems address only one specific disease and are therefore designed for the special circumstances imposed by this disease. Most of them were developed to support the treatment of patients with chronic heart failures like the previous mentioned TEN-HMS. There is a need for a generic and flexible system that can be used with a broad range of sensors and devices.

One example of such a system is a project that had the goal to develop a rule-based expert system for tele-monitoring patients with heart failure [94]. The system was designed to generate instructions and alerts based on the measurement of the patient's weight, blood pressure, heart rate and symptoms. They performed a lot of interviews with heart failure clinicians to develop the rule set for the expert system. The resulting system performed well in the subsequent trial for validation of the rule set. Although the systems performance was good, the development of the rule set was a very sophisticated process that resulted in one fixed rule set for tele-monitoring patients with a heart failure.

3.2.1 Big Data and Data mining

Data mining is the application of methods and algorithms to a data base in order to extract correlations or patterns in the data [95]. These methods are often used on a large, sometimes unstructured, data base that is called Big Data (cf. section 2.3). Big Data and data mining techniques promise a great potential to enable medical systems to use data and analytics systematically to identify deficiencies or inefficient processes. Generating optimized guidelines for the healthcare industry could improve care while reducing costs. Experts estimate that by both improving care and simultaneously reducing the costs for treatments, the opportunities for savings to the healthcare systems could add up to 30% of the overall budget [96]. Unfortunately, the healthcare industry is rather slow at adopting new technologies. This is mostly due to the high complexity of the data itself and the healthcare system generally. Therefore the use of data mining techniques is rather uncommon in medical systems.

IBM Watson is the most popular example of big data analysis. The development of Watson started in 2007 and gained a lot of publicity in 2011 by winning the TV game show Jeopardy. The system is built to analyze lots of unstructured data, most of it in natural human language. The goal is to understand the words and their context, combine the information and draw conclusions from the gained knowledge. Afterwards it is able to answer questions in this specific domain, just like humans would do. Watson is already used in medical applications to analyze scientific publications, gain the latest knowledge and progress in medical processes. Watson is used to create new hypotheses upon the gained knowledge and to assist physicians by answering medical questions or creating diagnoses on the basis of given symptoms and their context. All hypotheses are given with a value of certainty for the correctness of the hypothesis [97]. An interesting field for data mining is the identification of functions in the human genes. Like the "Human Knockout Project"[98] where the researchers try to find families with special defects in their genes, so called loss-of-function variants, to correlate the genetic representations for body functions. This helps to develop new medication or to gain knowledge about genetic diseases.

3.2.2 Application in medical contexts

In contrast to the use in other fields, like economy or marketing, data mining in medical contexts has some crucial different features [99]. First of all, medicine is a safety critical context [100] where wrong decisions can have a large impact. This creates a high cautiousness among the participants that create and use the data base, even to the point that only few data can be created due to high costs of security precautions, involvement of a lot highly skilled personnel or just the lack of patients eager to participate. Additionally medical data has usually a higher amount of uncertainty than other data [55]. These can result from faulty measurements, missing data or the fact that much of the desired information is only available in textual form, written by physicians. To overcome these difficulties domain specific knowledge is utilized or models and methods are thoroughly selected to match the problem description while particularly encoding the knowledge [101].

3.3 Challenges of telemedicine

Obviously, there are several challenges in the use and creation of telemedicine systems which need to be solved by a new system. One of the biggest problems is that telemedical systems are usually very specifically designed to resolve one problem or the help with certain aspects of one disease. Additionally, these systems mostly offer very few interfaces for data exchange or data formats, that are not compatible with other systems. That creates a lot of isolated applications that cannot interact with each other in order to form a telemedical system that can be used for all different tasks and diseases.

In most of the mentioned projects the vital parameters of the patients were measured once a day in a predefined setting. Afterwards they were collected by a stationary local unit and transmitted to a central server. These telemedical systems are typically limited to one specific disease and have been designed for specific circumstances. In the meantime there are other research projects that aim for more generic telemedical infrastructures (e.g. [102]) but there is still no solution for combining different systems in the unstructured environment of telemedicine. Most of the telemedical applications are pilot projects that are not financed any further after the project phase or were not able to establish a sellable business model [103, 104]. This is also owed the fact that health insurances do not provide possibilities to account for telemedical services.

The mentioned projects were only a small section of the existing telemedicine systems, but they show that the use of telemedical systems has medical and economical advantages. Existing realizations of telemedical systems are limited to support treatments of specific diseases. Consequently there is a need for a telemedical system with a highly modular structure that offers a generic and flexible infrastructure that is capable to support the treatment of multiple diseases with different requirements in one system. Furthermore the system need to be mobile and able to support the patient in their daily life and usual environment of living while continuously keeping track of the patients health status.

Another problem is the issue of medical records. The data that is recorded and transmitted is often very unstructured. To use the data in the clinical routine, it has to be transfered, converted or even re-entered into other systems. Sometimes this process is necessary multiple times per record. The telemedical systems should make use of standardization and try to be as generic as possible to avoid being isolated applications. That can also lead to a merged health record for each patient where all relevant data is collected and can be used by clinical personnel and other care services to provide a holistic image of the patient and allow an individual and optimal treatment.

Data mining approaches are very promising to aid at diagnosing diseases or optimizing the treatment. Due to legal aspects the usage of such systems is currently not possible in countries like Germany. Even the approach of IBM Watson, that gives multiple suggestions with probability values to chose from, would be a de facto diagnosis because people tend to chose the top suggestion all the time. In European countries it has to be a physician that is responsible for the diagnosis and the planning of the treatment. It is now to be clarified how intelligent systems can support the medical personnel in a way that can be arranged with the legal situation or how laws have to be adapted.

Chapter 4

Building a generic telemedicine system

We built a telemedical system that is capable of handling various existing medical sensors and provides interfaces to the different actors of such a system. The use cases, design, implementation and evaluation are elements of this chapter.

4.1 Outline

Telemedicine is an emerging trend, driven by the technological development and the growing need for an efficient healthcare. Telemedicine enables physicians to evaluate the condition of patients from a distance or contacting colleagues to discuss medical issues. We defined and implemented a new telemedical system that aims to answer the following questions:

- Who are the main actors in a complete telemedical system and what are their needs?
- What are the requirements for medical systems to be easily integrated in a telemedical system?
- How can medical expertise adequately be transfered over distances?
- How can the technical prerequisites be lowered or simplified?
- Can a telemedical system be completely abstracted from any characteristics of specific diseases?

Figure 4.1 shows the main aspects of the telemedicine system. The patient on the left side resides at his home and is equipped with COTS medical sensors and a smartphone. The smartphone collects the data from the sensors and provides a user interface for interaction with the patient (see section 4.3.3.2), like communication with doctors, viewing his data or filling questionnaires. The communication link to the backend of the telemedicine system (red line) is provided via wireless technologies and examined in detail (see section 4.9). The backend is responsible for storing and analyzing the data as well as providing interfaces for all users and other systems to connect (see section 4.3.3.3). On the right hand side the telemedical workplace

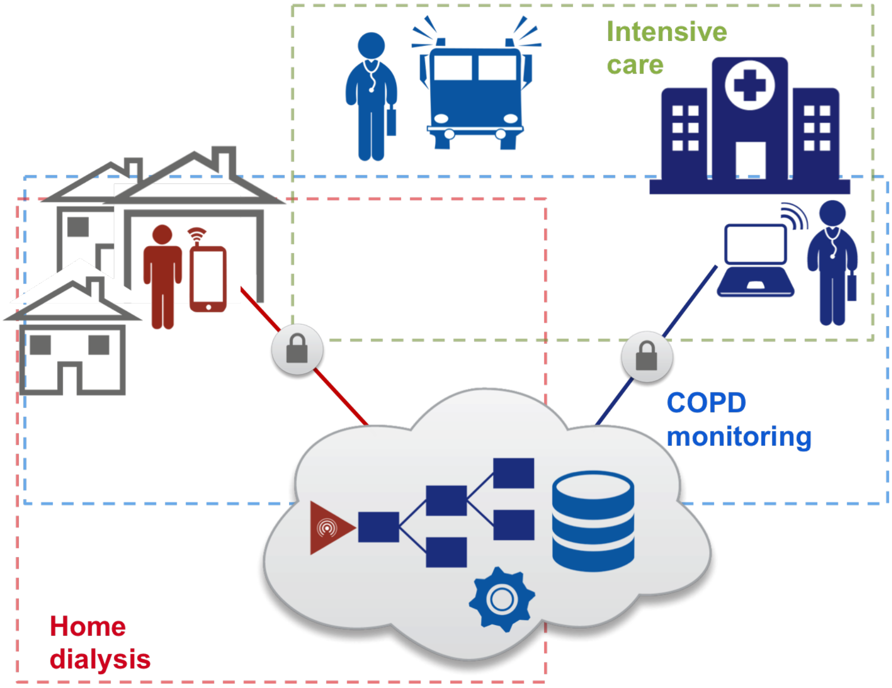


Figure 4.1: Main aspects of the telemedicine system

is depicted, where medical personnel can access the data of their patients, perform analysis on the data or communicate with the patient (see section 4.3.3.4). Above are other hospitals, medical personnel or emergency services that can be contacted and shared information with. The system design was based on three different use cases to create diverse requirements that lead to a generic system while being able to test the system in specific scenarios. The use cases are described in detail in section 4.2. Their main focus is depicted in the figure 4.1. The blue dotted line represents the use case of the COPD home monitoring, where the focus lies on the transmission and display of the sensor data. The home dialysis use case (red dotted line) focuses mainly on sensor data acquisition, user interfaces and local autonomy at the patients side. The main aspects of the third use case, intensive care (green dotted line), are a fast and easy data transfer and communication between medical personnel in different locations.

4.1.1 Motivation

The demographic change in our society and the lack of highly qualified medical personnel will lead to an insufficient medical care, especially in rural areas. The medical expertise accumulates in some small centers and is not available to the masses. The development of telemedical systems is a way to cope with this trend. These systems promise to bridge the spatial gap between doctor and patient or two doctors in order to perform a treatment or an exchange of expertise. Telemedicine also allows to reduce the costs of treatments by lowering transportation costs for the patient, reducing medication and preventing hospitalization. It can also optimize the doctor-patient ratio and reduce the workload for physicians.

4.1.2 Goals

There are already a lot of telemedicine systems in development and some even in productive use (see section 3.1). Although the underlaying technologies are very similar for every telemedical system they are not compatible and isolated applications. We came up with the following primary design goals for our system to go beyond the state of the art:

- Create a generic telemedicine infrastructure that is independent from the type of disease that should be treated.
- Involve all the stakeholders of such a system, like medical personnel, patients and nurses. Getting input and feedback for the systems user interfaces and concepts to develop a system that is accepted and useful in the daily routine.
- Take advantage of the fast improvements in consumer electronics by using standard COTS hardware and commercial medical sensors.

4.2 Use cases

Although we want to achieve a generic telemedical system that is independent of a specific disease we needed to focus the development on some use cases. That allowed us to define requirements that can be tested afterwards to ensure the quality of the system. We also could record data from some patients, that were included in the tests, to use them for testing analysis functionality of the system. We picked three completely different use cases, to get requirements that enforce us to consider all use cases in between and get a generic system. Figure 4.2 shows the wide field of medical use cases for a telemedicine system. Even though it is only an excerpt of all possible use cases, it shows the variety of requirements the different use cases have. We chose the use cases COPD monitoring, home dialysis and intensive care as the are the edge cases in terms of mobility and time criticality. We therefore subsume all the other cases if we meet the requirements of these three use cases.

4.2.1 Application in Home Dialysis

As medical devices like home ventilation or dialysis machines already reside at the patients home and communication links can easily be established, the next logical step is to fine tune and control device parameters remotely and to supervise the therapy from the distance. This would allow to reduce the presence of highly qualified personnel in dialysis centers or to optimize the ratio of personnel and patients.

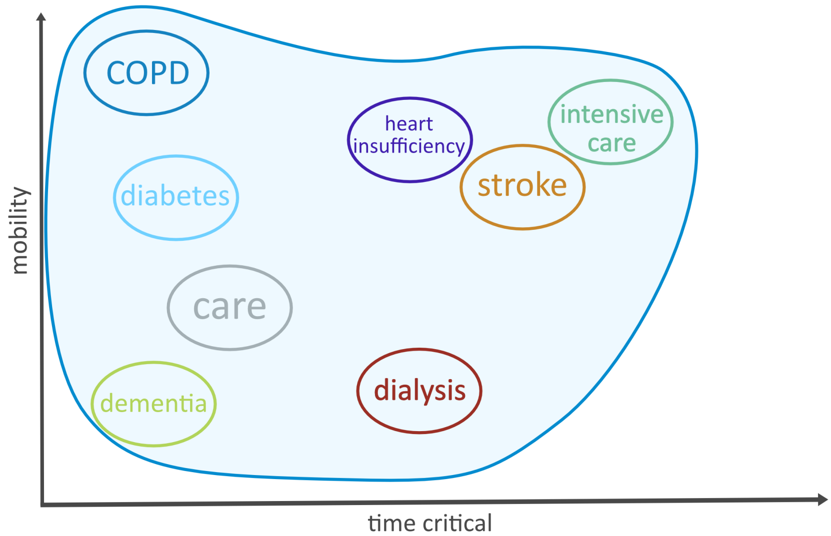


Figure 4.2: Strategically selected use cases lead to a generic system

It could also lead more patients to home dialysis, which is already possible but yet barely performed. A lot of patients fear problems or situations getting out of control. The feeling of being well supervised and the fact that the treatment is monitored and experts can help anytime lowers such fears and could bring more people to home dialysis which is better for the patients, the medical personnel and the healthcare system. But any changes of machine parameters or the treatment must be based on a an integral knowledge of the patient's and machine's status and medical expertise. Despite regulatory requirements which aim to eliminate any risk of harm to the patient, also the technological requirements have to be investigated. The dialysis treatment is one possible field of application for both patient monitoring and controlling machine parameters. Figure 4.3 shows the sensors and actuators of a modern dialysis machine manufactured by Fresenius Medical Care. The dialysis machine is a big blood pumping and filtering device, that is mainly used to extract toxic particles and water out of the patient's body. The dialysis machine inherits multiple sensors for various parameters like:

- arterial and venous pressure for detection of leakage and inaccurate puncture
- blood filtration rate and blood flow
- ultra-filtration (amount of extracted water)
- temperature of arterial and venous bloodstream
- visible detection of blood viscosity
- failure detection like bubbles/air inside the blood tubing, insufficient blood flow and others

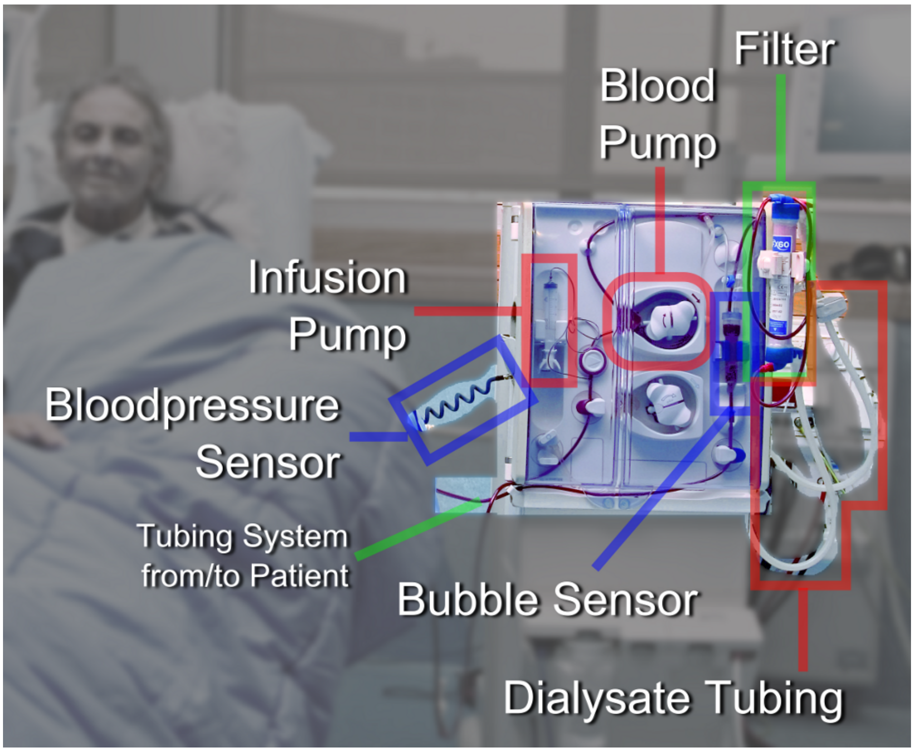


Figure 4.3: Dialysis machine with highlighted sensors and actuators.

- blood pressure

Additionally the machine provides several controllable actuators which allow the manipulation of the following parameters:

- blood pump (desired flux)
- ultra-filtration rate (desired water extraction rate)
- treatment duration (e.g. 2 to 8 hours)
- infusion pump (anti coagulation medication, Heparin)
- blood temperature (heating or cooling the blood inside the tubing system)
- composition of dialysate liquid (pH, bicarbonate, electrolytes, temperature)

In figure 4.4 the different components and actors of a telemedical supervised dialysis are displayed. Essential external sensors e.g. a weighting scale and the dialysis machine provides various parameters that are transmitted via personal area networks like Bluetooth to a smartphone. The smartphone collects, processes and sends it via wide area networks to the supervising personnel. The communication links can be realized with mobile and wireless communication technologies like the ones discussed before. The requirements for telecommunication aspects as well as for gathering and representing the medical data are examined. One other major aspect of ongoing

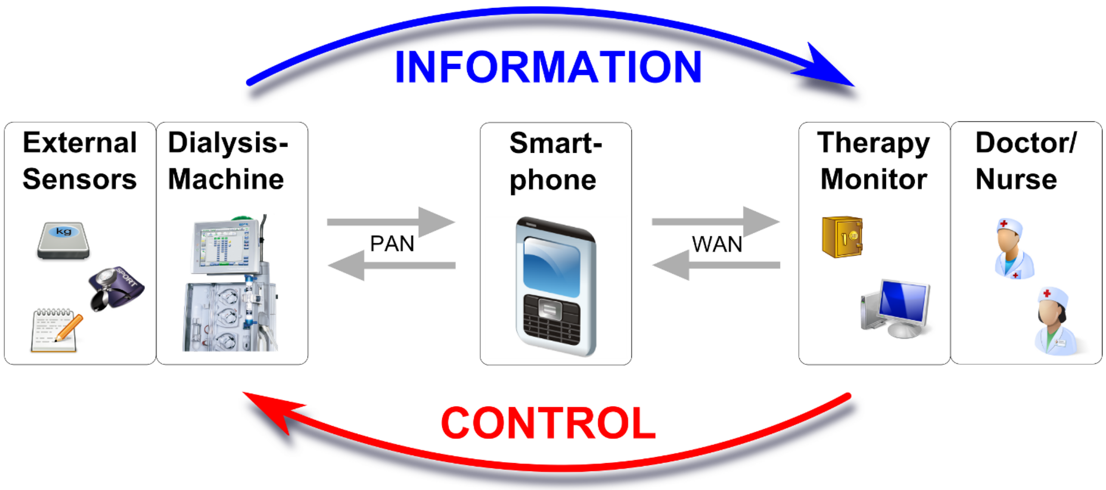


Figure 4.4: Tele-health control system - example for home dialysis

research is to re-establish and improve the interactions and communication between the patient and his attending doctor due to the fact the patient is no longer visiting the dialysis center three times per week.

4.2.2 Remote supervision of COPD patients

Our system was implemented as a module for a remote support system of COPD patients [14] (see section 2.2.1). During the research project, patients were equipped with a set of sensors consisting of a pulse oximeter, blood pressure monitor, scale, activity monitor and a peak flow meter. In addition to the sensors a medical ventilator was integrated as an actuator. All devices are available as COTS standalone systems with integrated communication interfaces. A commercial smartphone was used as data acquisition unit. Additionally, the smartphone provided a questionnaire for quality of life questions. Figure 4.5 shows the interaction between the different parts.

For several weeks, patients measured their vital parameters with the provided sensors while the smartphone collected all the data. Activity and oxygen saturation were measured continuously for long time periods. Other parameters like blood pressure and weight were measured once a day. The collected data was automatically transmitted to the server of the telemedical center whenever new data and a communication link was available. Initial analysis functions were implemented and tested in the central analysis server to gather additional information like the number of oxygen desaturations at night. Alarms could be generated for specified conditions. Via the telemedical work place, a nurse supervised the patients and provided medical support when needed. Filtering functionality allows the physician to let the patient list be ordered by their health status. The definition of the health status can be set by the physician to provide maximum flexibility.

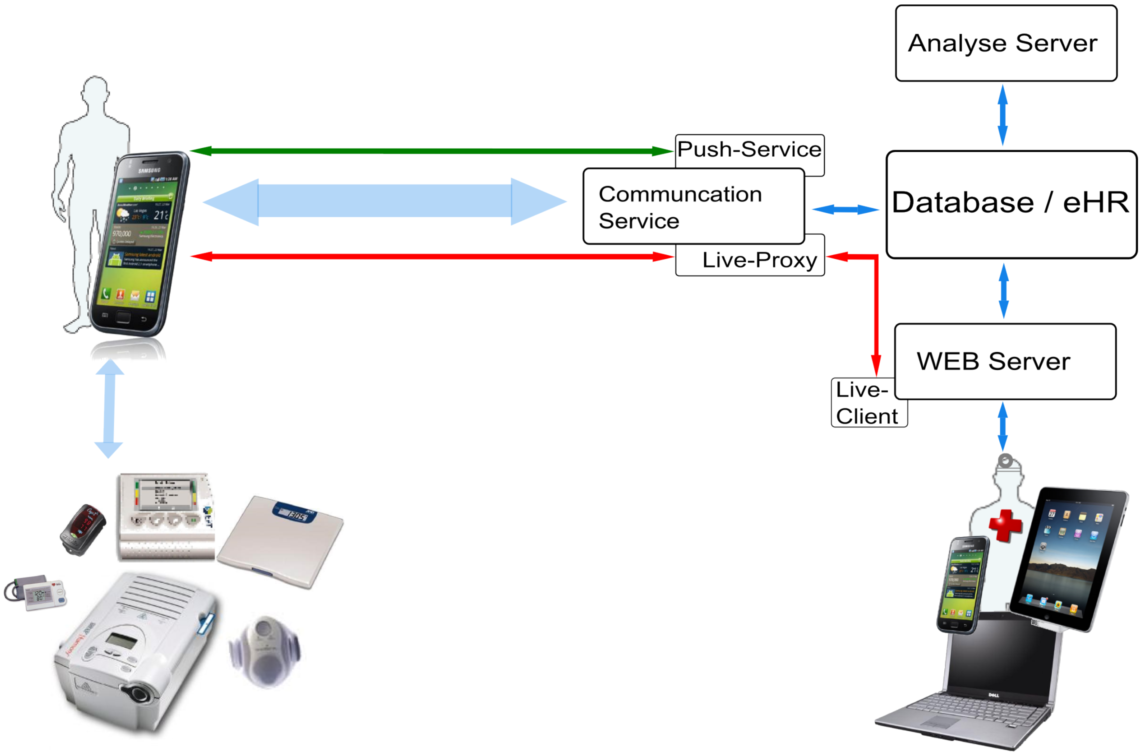


Figure 4.5: System overview for the remote support system of COPD patients

The smartphones internal sensors can also be used to replace other sensors. The activity of the patient can be measured with the gyroscopes inside every modern smartphone [105]. The on-site data analysis enables to react to uncertain medical situations in real-time, like triggering an additional data transmission to the Tele-Service-Center for immediate medical supervision.

On the clinical side, a nurse was using the telemedical work place to view the patients data. The data was viewed and checked for abnormalities. The telemedical center had several time slots where patients could contact the center for discussing technical difficulties or abnormalities in the data. The personnel at the telemedical center also tested the usability and the technical functions of the telemedical work place and gave continuous feedback to the developers. One part of this feedback process was a questionnaire in combination with an interview of the medical personnel. The questionnaire in appendix D was used for the home dialysis scenario.

For the described setup a wide set of sensors was integrated. During the test phase, we were able to show, that the proposed system is capable of supervising COPD patients during their daily life. We hope to reduce the set of sensors during a larger and longer test or clinical trial in the future with a detailed analysis of the data. The goal is to find the best prediction for the patients health status with as few sensors as possible to relieve the patient while preserving the quality of the data.

The user interface design and handling on the patient device was optimized for the target group of patients. Often these are elderly patients with physical restrictions. Therefore the handling of the Android smartphone was adapted with a special launcher and a single main application. With the restricted access to system components the patients were not afraid to “do something wrong”. This provided a feeling of safety to the patients. After starting the main application all communication to the sensors was handled autonomously. The patients just used their sensors as usual. Via a visual feedback, the patients easily recognized which sensors were used and which are next. After finishing the daily routine the patient got feedback over upcoming events, e.g. the next measurement or an appointment with the physician, and could leave the application. With this one-click-design a very high acceptance and compliance was established and the patients got the feeling of being well supervised.

4.2.3 Supporting intensive care units

The remote support scenario of intensive care experts (described in section 2.2.3) should be improved with a telemedical system to shorten reaction times and provide the expert team a better understanding of the patients state. Figure 4.6 shows the extended information flow between the two hospitals. The system should replace the fax, and provide a possibility to transfer the patients data in real-time to the experts. F urther a transmission of pictures should be possible, to allow the requesting medical personnel to provide additional information (e.g. images of the respiratory monitor). The voice communication should be extended with a possibility for video communication. This allows to show some details of the patients environment and enables the experts to guide the personnel at the remote hospital as they are seeing the remote place.

Another design goal of the system is to be very easy and robust, because it is used in an environment that is usually very hectic. Therefore a simple and self explanatory design of the user interfaces is needed. It is also necessary, that the system does not need specific hardware. The peripheral hospital have very low budgets and are not able to equip their intensive care units with expensive specialized hardware for remote support scenarios. We decided to build these functionalities as an application that runs in a browser. This enables to run the system on a huge amount of different devices and platforms, even on mobile ones, which creates a very low technical and financial barrier. It is also possible that the system is used from private devices or in other contexts like emergencies.

4.3 System design

4.3.1 System Requirements

While we built a generic system for supporting various diseases we focused our development on sample applications: remote supervision of COPD patients, telecounseling for diagnosing patients in intensive care and assistance for patients performing their dialysis treatment at home. We came up with requirements for the telemedical system by intensely analyzing these applications. The support of other

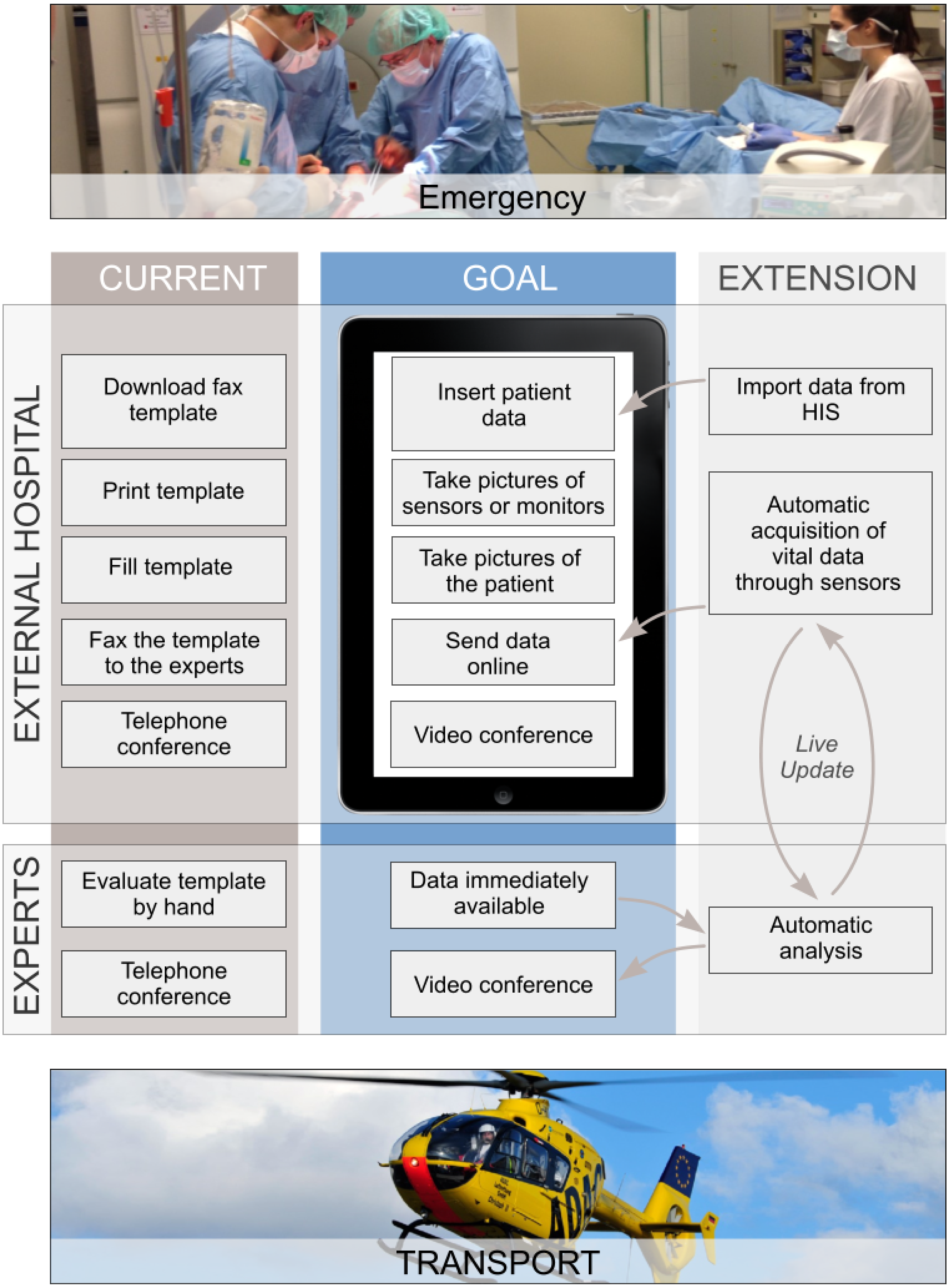


Figure 4.6: Improved work-flow and information exchange at an intensive care support scenario

diseases may impose some other requirements, but the generic approach of the system allows a fast and easy extension of the existing modules and implementation and integration of new ones.

4.3.1.1 COPD and home mechanical ventilation

Important sensors and parameters: Table 4.1 shows the set of sensors which is mandatory to identify the state of health of patients with a respiratory system disease (e.g. COPD) using a mechanical ventilation system or not. The table in appendix A shows all the sensors, that were considered during the selection process and the criteria that were used to choose the right sensors for this use case. To make high quality diagnosis physicians specified minimum sample rates for the defined sensors. Examples of these sensors are shown in figure 4.7.

Table 4.1: Sensors, sampling rates and vital parameters for COPD

Sensor	Sampling rate / transmission rate	Parameters
Pulse Oximeter	Continuous / Daily	Arterial oxygen saturation (S_aO_2), Pulse
Activity Sensor	Continuous / Daily	Activity
Scale	Daily / Daily	Body weight
Aeroplethysmograph	Daily / Daily	Vital capacity, Tidal volume (PEF, FEV1, FVC, MEF25, MEF50, MEF75)
Mechanical Ventilation	Continuous / Continuous	Usage (Compliance), Breathing rate, Leakage, Tidal volume
Questionnaire CAT 12 (see appendix B)	Daily / Daily	Subjective symptoms, Breathlessness, State of Health

System requirements: To reduce medical therapy costs with simultaneous improvement of the treatment quality, modern telematic techniques could ensure success. These techniques shall provide the possibility of continuous contact with medical specialists and gathering data on a secure and adequate data storage. Patients are able to remain in familiar surroundings with parallel medical observation. The acquired parameters are analyzed continuously by evaluation algorithms which can generate emergency calls, alarms and other instructions to solve abnormalities. The requirements to achieve this were discussed with the medical personnel and identified

Figure 4.7: Medical sensors, left: Pulse oximeter, right: Spirometer

in several interviews with possible users of the system (see the interview protocol in appendix D). Thus, the following requirements are identified:

1. **Identify patient status:** Different patient related data should be collected by a capable data acquisition unit. The measurements are gathered via distributed sensors communicating over standardized protocols and transmission technologies with the data acquisition unit. The subjective symptoms of patients can be captured via predefined questionnaire. The sampling frequency differs depending on the particular parameters between hourly, daily and monthly.

2. **Flexible data transmission:** The collected data should be transmitted to a data storage where all relevant information related to patients are stored. The transmission unit should be able to handle abnormalities like bad data links. Depending on ambient conditions, the data transmission unit should be able to reduce the amount of data by preprocessing the collected data. In case of interrupted links a specified amount of incidental data should be buffered on the transmission unit for a given time. The transmission should be safe, secure and assure protection of data privacy.

3. **Adaptable data management:** The data management system should be able to store all relevant information like all different kind of sensor data or questionnaires. Therefore the system must be always available and have enough memory capacity. The data management system should also be safe, secure and assure protection of data privacy.

4. **New medical awareness:** Intelligent evaluation algorithms should try to identify new medical awareness (e.g. risk factors) by long-term data analysis.

5. **Improvement in efficiency:** Adaption of a telemedicine center with medical specialists to reduce unnecessary medical consultations. The center specialists

should be able to monitor the patients via a adaptable user interface, give feedback, transmit instructions and invite patients for medical consultations only if necessary.

6. **Improvement of compliance:** Adequate interaction concepts on patients side should improve the compliance. Patients should be informed if the medical treatment takes effect.

4.3.1.2 Home dialysis assistance

Important sensors and parameters: The following parameters are essential to assess a single dialysis session or the whole treatment. The goal is to track both the patients health status and the dialysis machine data and status. Body weight is an essential parameter which is measured twice, before and after the dialysis treatment to define the extracted amount of water. A blood analysis is performed periodically (weekly - monthly) to determine the patients levels of potassium, bicarbonate, sodium, calcium, sugar and others. These values are needed to define the electrolyte concentrations for the dialysis liquid. Inadequate levels of potassium inside the dialysis liquid could result in heart failures. The blood pressure is measured every hour during dialysis, to monitor the patients cardiovascular system. The dialysis machine itself already inherits multiple sensors:

- Arterial and venous pressure for detection of leakage and inaccurate puncture
- Blood filtration rate / Blood flow
- Temperature of arterial and venous bloodstream
- Failure detection like bubbles/air inside the tube system, insufficient blood flow and others

Table 4.3 lists the sensors and transmission rates used for the home dialysis assistance after discussing possible sensors and requirements with the medical partners (see appendix C).

System requirements: The aim is to create a system that is accepted by all stakeholders. Therefore the system has to be easy to use and offering ambient assisted living. It must assure an equivalent dialysis quality at home as in a dialysis center. In order to design a system which provides such a dialysis treatment at home some requirements on the system have been identified:

1. **Autonomy:** One major requirement is that the system offers autonomy. It has to assist patients, to live at home and treat themselves with minimal need for help of further persons.

2. **Patient and machine status:** The telematic assistance is based on patients vital data gathered by various distributed sensors. Furthermore relevant

Table 4.3: Sensors, sampling rates and vital parameters for home dialysis

Sensor	Sampling rate / transmission rate	Parameters
Scale	Twice per treatment / Daily	Weight
Blood pressure monitor	Hourly / Daily	Blood pressure
Dialysis machine	Continuous / Daily	Arterial and venous pressure, Blood filtration rate, Blood flow, Temperatures, Failures
Laboratory	weekly - monthly / when available	Blood analysis ()potassium, bicarbonate, sodium, calcium, sugar)

dialysis machine parameters can be retrieved and in some cases possibly be fine-tuned under medical remote supervision to provide optimized treatment conditions.

3. **Data transmission:** The distributed sensors transmit their data as being measured to a data collection and presentation device. For this application there is no need to continuously transmit data to a service center. In case of error events, caused by the machine or problems during the treatment a connection to the supervising dialysis center or doctor shall be established. The connection can also be established on the patient's or the doctor's request. It is commonly realized via a wired or wireless broadband connection.

4. **Medical supervision:** The doctor shall be able to monitor a patients dialysis treatment to support the patient at home in order to provide a feeling of safety to the patient. The supervision is adapted with respect to the autonomy of the patient.

5. **Adaptable dialysis regime:** To allow an adaption of the dialysis regime the doctor can perceive current values and data of treatments. If an adaption of the regime parameters is necessary the new regime is transmitted to the patient who can use it for the next treatment.

6. **Communication:** An optimized support for the patient can be reached by several methods of communication. A synchronous communication link can be used to allow the patient and the doctor to speak to and see each other. In contrast an asynchronous communication can be used to transmit non-critical data that is used to adapt the dialysis regime or monitor long-term progression of parameters.

To cover all the system requirements an innovative and modular system architecture was specified which allows a high grade of interoperability. The following picture (figure 4.8) gives an overview of the components and interfaces.

4.3.1.3 Intensive care

Important sensors and parameters: The remote support of intensive care personnel requires no additional sensors to be connected to the system. The important parameters that need to be supported and transmitted by the system can be divided into the following three groups:

1. **Questionnaire:** The interesting parameters of the patients vital data, therapy information, medication and others are combined in the questionnaire. The different parts must not be available at the same time. So the system has to support multiple data transmissions that are merged into the report of the patients data at the experts side.

2. **Images:** Some important information can not be transported via the questionnaire. The possibility to transmit pictures is seen as a key feature by the medical personnel holding the expertise.

3. **Live communication:** Audio and video communication between the two hospitals can provide the last bit of situation awareness that is needed by the experts to get a holistic understanding of the patients state and to decide the best strategy of therapy for the patient.

System requirements: The intensive care scenario has different requirements to the telemedical system than the other ones. Here the focus lies on real time data transmission and communication. The system has to provide a possibility to insert the data of the questionnaire (see appendix E) and transmit it to the experts. Additional transmission of images have to be supported. It is also necessary to support real time communication with video and audio channels. According to German laws and privacy restrictions the data transmissions have to be secured by encryption and the data has to be protected from misuse. This leads to the following requirements:

1. **Transmission of data and images:** The two hospitals need to exchange data and images without media discontinuity.

2. **Support of video and audio real time communication:** A live communication via audio and video has to be possible without the need of expensive, specialized hardware. These communication links need to adapt to the current network situation and provide functionality for graceful degradation of the transmission quality to assure a connection as long as possible.

3. **Platform independence:** As the infrastructure in the external hospitals is not known beforehand, the system needs to run on a broad variety of systems.

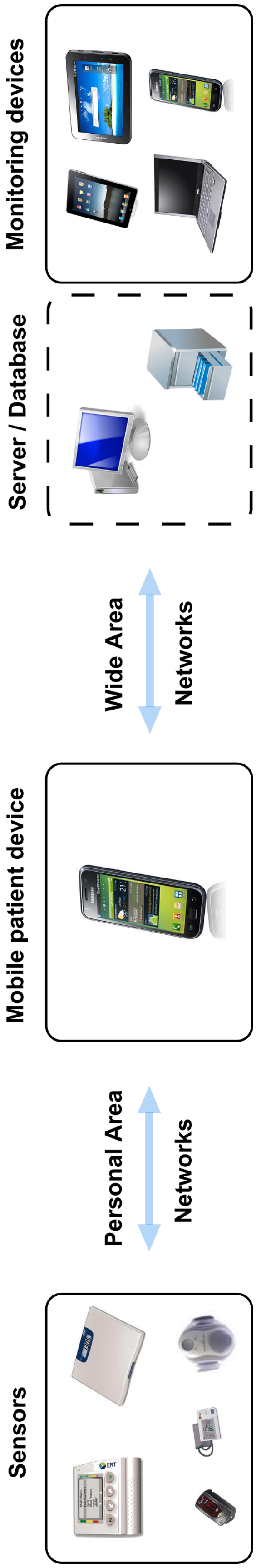


Figure 4.8: Conception of a generic telemedical system

Platform independency is the key for high acceptance as the users are flexible in the choice of hardware.

4. **Secured data transfer:** All data transfers have to be secured by state of the art technologies due to terms of privacy and security. Sensible data should not remain on the users' devices.

4.3.1.4 Summary

The different requirements described above show, that a generic, modular and expandable telemedical infrastructure is needed to support treatments for different diseases. On the one hand some requirements are identical on the other hand requirements are specific for different medical conditions. In figure 4.9 an overview over a generic, modular telemedical infrastructure is shown. This system is able to meet the multiple requirements of different disease treatments. The core of the system is the modular telemedical infrastructure, that takes care of communication links, data transmission, data security and safety as well as all basic operations. This infrastructure can be extended with different modules to support the treatment of different diseases. Furthermore the system can be extended by a Tele-Service-Center, that is staffed with a multidisciplinary medical care team. The infrastructure supports different end users like patients, the attending doctor of the patient or specialized clinical doctors that are connected to the system over WAN connections. The system supports different views on the data and allows a granular configuration of the various roles of the actors inside the system. On the patient side a data acquisition unit (e.g. a smartphone) collects the data of the sensors of the patient via PAN connections and is connected to the infrastructure via WAN connections. Based on the generic and modular architecture of the system all communication links, data transmissions, used sensors, data analysis and all other operations can be defined for different disease treatments. If necessary these operations can be changed and adapted for each single patient to fit the individual needs.

4.3.2 Concept

Over the last decades, huge effort has been put into developing medical sensors for many vital parameters. As current trends show, these sensors are increasingly equipped with modern communication interfaces like Bluetooth. By now several high quality sensors are available with integrated communication interfaces as COTS devices. In addition to the development of a wide spectrum of medical devices, COTS hardware evolves continuously. Therefore the usage of these devices offers new possibilities for the field of telemedicine.

Attempting to support the monitoring of multiple diseases in a single system brings up several challenges: Every disease is diagnosed with the analysis of a special set of vital parameters. These vital parameters can be measured with a wide set of sensors. In the area of near field communication, the integration of COTS sensors is still a big problem in terms of usability and robustness due to the heterogeneous

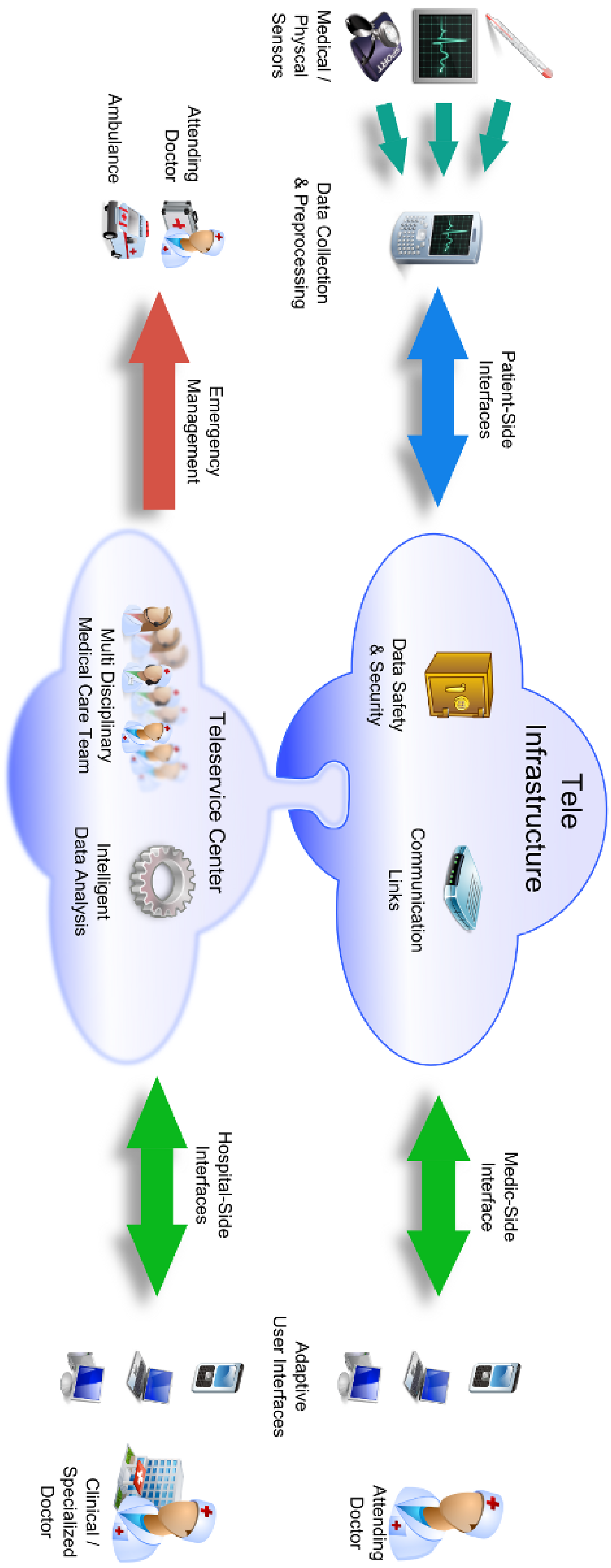


Figure 4.9: Generic telemedical infrastructure

communication behavior and protocols. For wide area connections, different devices have different requirements regarding connection speed, transmission intervals, and whether a bidirectional communication is necessary. The support of mobile patients introduces additional requirements and problems. With the increased mobility of the patient the surrounding parameters are more and more unstable. Nowadays, projects are often limited to predefined circumstances in which the patient is located at a specific location with known network parameters. The patient measures the parameters only once or twice a day in these settings. We aim to achieve continuous measurements during the whole day without limiting the patient's mobility. This means for example that network parameters might change. These requirements all need to be considered. With an adaptable system, we aim to support mobile patients with every needed combination of sensors and actuators.

Figure 4.10 shows an overview over the described modular telemedical infrastructure that was implemented. This system is able to meet the requirements for supporting treatments of different diseases. The patient is monitored and assisted by established COTS medical devices. A data acquisition unit, which runs a telemedical application on COTS hardware, is the bridge to the Tele-Service-Infrastructure. It collects all sensor data, stores and preprocesses it. This hardware might be a COTS smartphone equipped with a high power central processing unit (CPU), sufficient storage, and several components for wide area and near field communication. The central Tele-Service-Infrastructure offers multiple communication services, data storage, security, safety and central analysis. Through a web based application, world wide access to the data is provided to the doctors and nurses in charge. The presented system offers two main advantages: First, supporting the treatment of multiple diseases due to the integration of versatile COTS medical hardware and second, supporting mobile patients in their daily live due to the integration of modern mobile consumer electronics. Furthermore, the system enables bidirectional communication of different types, including a live remote supervision and it offers an on-site preprocessing and backend analysis of data.

4.3.3 Main components

4.3.3.1 Sensors and actuators

Since various medical companies put much effort into developing new medical sensors, we propose to use this development for new telemedical applications. Therefore, we suggest to use COTS sensors and actuators that already offer communication interfaces. With this approach, a customized set of sensors and actuators can be chosen to monitor the current health status for each disease and patient. The set of sensors can include standards, such as a weighing scale or a blood pressure monitor, but also more specialized hardware such as an ECG, pulse oximeter, or even a medical ventilator.

Table 4.5 shows the set of sensors which is mandatory to identify the state of health of patients with a respiratory system disease (e.g. COPD) using a mechanical ventilation system or not. To make high quality diagnosis, physicians specified

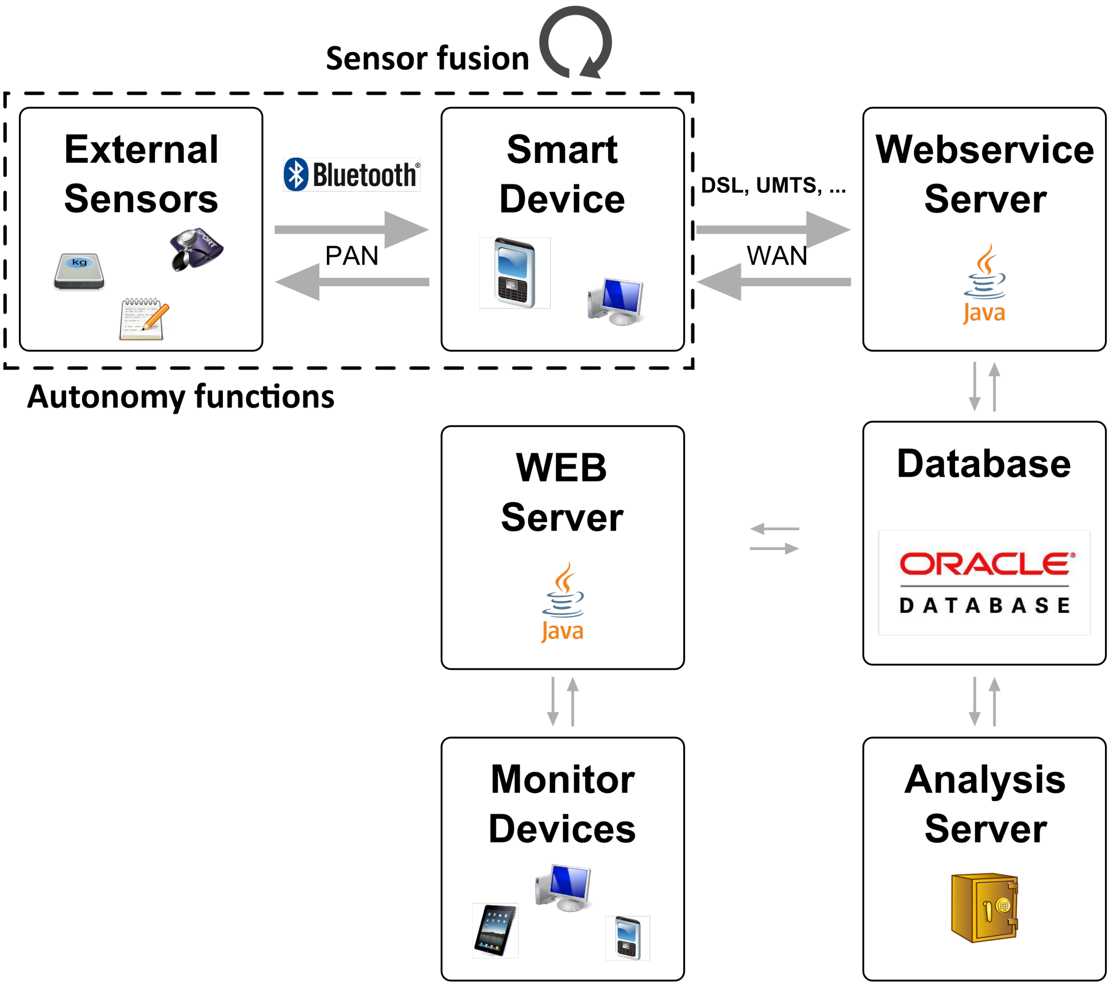


Figure 4.10: Component overview of the telemedical system

sample rates for the defined sensors. The used sensors are shown in figure 4.11. All sensors offer a wireless communication via Bluetooth. This offers the possibility for a very flexible transmission of the measured vital parameters.

Table 4.5: Sensors used in the project for measuring vital parameters of COPD patients

Sensor	**Sampling rate / transmission rate**	**measured parameters**
Pulse Oximeter (Nonin WristOx[2])	continuously during night / daily	arterial oxygen saturation (S_aO_2), Pulse
Activity Sensor (Aipermon)	continuously during day / daily	activity (slow, fast, distance, steps, ...)
Scale (A&D)	once daily / daily	body weight in kg and pound
Aeroplethysmograph (ERT AM1)	once daily / daily	vital capacity, tidal volume (PEF, FEV1, FVC, MEF25, MEF50, MEF75)
Blood Pressure Monitor (A&D)	once daily / daily	arterial and systolic blood pressure, pulse
Questionnaire	daily / daily	subjective symptoms, breathlessness, state of health

4.3.3.2 Data Acquisition Unit

The data acquisition unit acts as central patient side device and also as bridge to the telemedical infrastructure. This unit collects data from the local sensors. It stores and preprocesses this data before transmitting it to the central storage and analysis site in the Tele-Service-Infrastructure. Preprocessing the data on the device itself allows to perform sensor data fusion in order to detect anomalies or sensor malfunction and create autonomy functionality. To achieve this, we propose to use COTS hardware for the development of telemedical applications. The development of COTS hardware, like smartphones, is driven by consumer electronics and improves very fast in terms of CPU power, battery power, storage and communication technologies. Therefore these device offer a high potential at a rather low price. Figure 4.12 shows the increasing capabilities of smartphones. The data acquisition

(a) Pulse Oximeter (Nonin WristOx^2) [106]

(b) Activity Sensor (Aipermon 465 BT) [107]

(c) Aeroplethysmograph (ERT AM1) [108]

(d) Scale (A&D UC-321PBT) [109]

(e) Blood Pressure Monitor (A&D UA-767PBT) [109]

(f) Respirator (ResMed Stellar) [110]

Figure 4.11: Sensors used to monitor the patients vital status

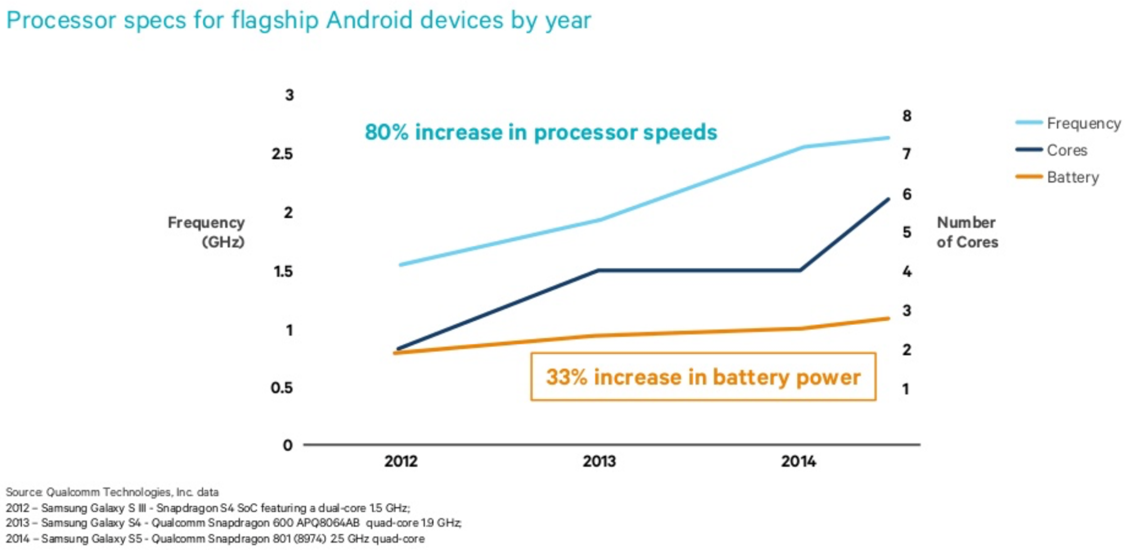


Figure 4.12: Development of smartphone performance, from [111]

unit and the local medical devices need to share a common communication technology. Modern medical devices offer Bluetooth communication which is also very often included in consumer electronics like smartphones. Therefore this combination is well suited. Upcoming standards like Bluetooth HDP and IEEE 11073 increase the interoperability of devices and make the integration of new sensors more feasible [34, 112].

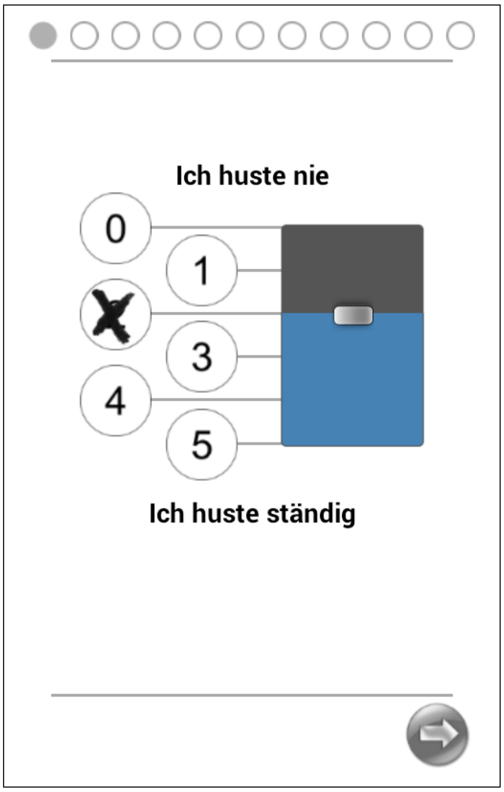
In the projects, the data acquisition unit was realized with an Android smartphone (Samsung Galaxy S). This device offers several connectivity standards like Bluetooth, Bluetooth HDP, WiFi, GPRS and UMTS. Furthermore, the smartphones have enough computing resources to handle and pre-process the gathered data. The software on the smartphone was implemented with the Android software development kit in Java [113].

To provide a comfortable usage of the system for the patient, the frontend devices like the smartphone plays a significant role. Therefore, an automatic measurement Activity is started when the app is started and the patient is supposed to measure vital parameters (figure 4.13a). The patient sees the sensors that he is supposed to use and can use them without any interaction. In the background the smartphone is building up the connection to all sensor devices. If the data from a sensor is collected successfully, the app marks the sensors with a green checkmark (figure 4.13b). If the patient needs help, he can press the sensor for an animated help how to use the sensor. Furthermore, an intuitive questionnaire was developed to keep track of the subjective status of the patient (figure 4.14a). If no interaction or measurement is needed from the patient the default screen is started (figure 4.14b), where he can see upcoming appointments, start new single measurements or call the Tele-Service-Center.

(a) Active measurement activity connecting to sensors and waiting for new data

(b) Finished measurement activity showing all transmissions successfully performed

Figure 4.13: Human-sensor interface on the patients' device



(a) Questionnaire for monitoring the subjective status

(b) Home screen if no measurement is needed

Figure 4.14: Interface of the patients device

4.3.3.3 Tele-Service-Infrastructure

The “heart” of the presented telemedical system is the Tele-Service-Infrastructure, or backend, with its service-oriented architecture providing different communication services, data storage and data analysis facilities. To support the treatment of several diseases in one system, a generic and flexible infrastructure was implemented.

The communication module is the bridge to the data acquisition unit on the patient side. Multiple communication types are offered by the module and can be implemented and used from the patients side device. The communication architecture will be presented in detail later. All patient reference data, sensor setups and acquired sensor data is stored in the central database. For the representation of the data in the data base, all users are assigned to roles like “nurse,” “physician,” “COPD patient,” “dialysis patient” and so on. For every role, multiple supervisors can be assigned. Therefore, the privacy of a patient can be guaranteed even if he has multiple diseases and wants specific supervisors to only check the data corresponding to one disease. The sensor devices of the patients are also assigned to one or more roles of the patients user. This structure allows to have a very detailed control of the access to the data and still support different diseases in this flexible and modular system.

For the system a generic and flexible infrastructure was implemented to provide a mobile communication between the central servers and the smartphone on the patient’s side. The infrastructure provides fast and bidirectional communication which is used for sensor data transmission, configuration and reconfiguration of the smartphone and sensors from the Tele-Service-Center and managing tasks and massages for the patient. For sensor data transmission two different transmission types were developed and implemented. One transmission type was implemented for the transmission of stored data up to several megabyte (MB) and one type for the live transfer of vital parameters. The usage of these transmission types can be changed by the needs of the users of the infrastructure at any time. Due to push notifications it is possible to store the data on the smartphone for some time and save energy, while still being able to activate the live transfer of the data on-the-fly and get the newest values of the patient on demand. The analysis of the different WAN communication networks like enhanced data rates for GSM evolution (EDGE), UMTS, WiFi in combination with DSL, etc., showed, that these networks are capable of transmissions with enough bandwidth to provide a live data transfer, but in a wireless controlled network it is important to keep in mind, that these network are more instable then local network connections [11].

4.3.3.4 Telemedical Work Place

A special telemedical work place allows physicians to work with the system and supervise patients. This work place provides general information about the patient and the medical status (see figure 4.15). The interface is divided in two main parts a header with the critical and important information and the lower part with different tabs for detail patient reference data, electronic patient records, diagnoses and treatments, alarms, sensor configuration and the measured sensor data. Furthermore, alarms generated by the automated analysis of the system are also shown here. The detailed view on the measured vital parameters (see figure 4.16) provides two parts. The lower part of the telemedical work place is showing the sensor data tab. The data is presented in a split-view. With the split-view the physicians can see detailed behavior of vital parameters and the context at once. With this information, the physicians in the Tele-Service-Center are able to provide optimal care for the patient. The telemedical work place was developed as a web based application since this offers world wide access to the data without specialized hardware. Through this web application, different actions on the data acquisition unit can be triggered, like the collection and transmission of sensor data or even a bidirectional real-time data link. In order to remote control specialized hardware through this live data link, a live client can be started inside the web application.

4.3.3.5 Analysis Server

For easing the burden of the physicians, an automated analysis was implemented to generate alarms in critical situations. The automated analysis is capable of detecting unusual developments of vital parameters of the patient like desaturations in the oxygen levels of the patients. The automated analysis of patient data is discussed in detail in chapter 5.

4.4 Hardware

COTS smartphones combine PAN and WAN communication technologies and can be used to collect data and transmit them. In example current smartphones based on Android, Windows Mobile or iOS are programmable and provide several communication platforms like WiFi, UMTS and Bluetooth which can be used for different communication ways to transmit data to another device. Based on these features smartphones are used to collect the patients vital parameters and connect the patient to the telemedical infrastructure. Smartphones also allow a direct conversation in combination with a visual feedback so that the doctor can assess the patients health condition through a dialog or a questionnaire. In summary, modern smartphones can be used to close the feedback loop for the patient and offer a high flexibility. In view of the features smartphones have a good cost-benefit ratio and are optimal for the described applications. Most of the modules are platform independent and can be accessed from COTS hardware like smartphones, tablet PCs or standard computers. The users can benefit from using mobile devices to be flexible and use the integrated hardware like senors, communication technology or cameras.

4.5 Database for data management

To store and manage the data acquired via sensors, modern databases are used. The databases correspond to current regulations on safety, security and data privacy.

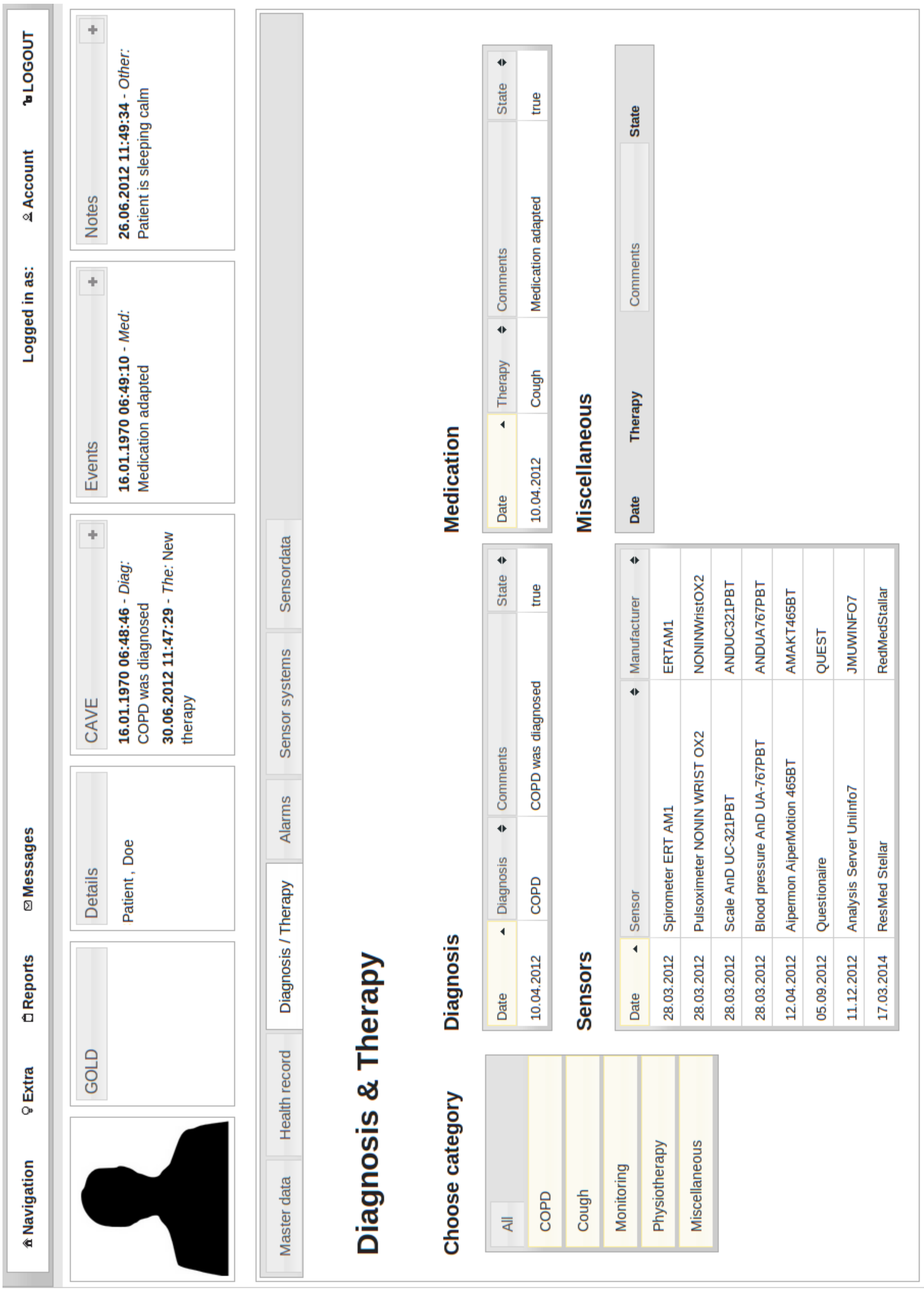


Figure 4.15: Telemedical work place showing general information about the patients diagnosis and treatments

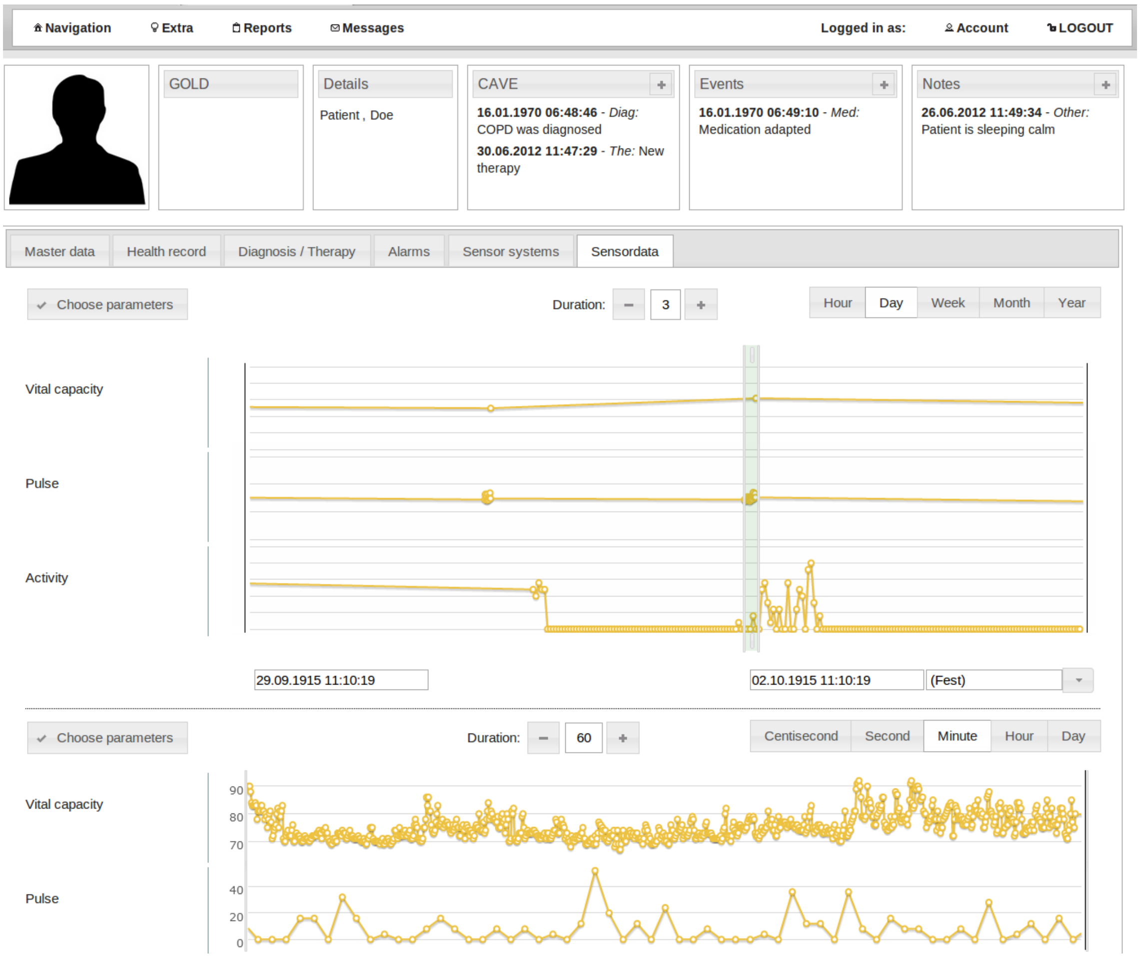


Figure 4.16: Detailed view of the sensor data

With the enormous amount of data now available intelligent evaluation algorithms can identify new medical awareness by long-term data analysis (cf. chapter 5). To support the modularity of the system a generic database meta language was developed to store the different types of values. For a proper management of users, views and rights the database design was discussed and refined several times to ensure data privacy and security even on the lowest levels. Each actor of the system has specific roles that enables them to access or change sets of data. Patients have read-only access to their own data while medical personnel has access to all data of their assigned patients. Researcher can get anonymized patient data for big data analysis. The patient can grant access to his data to doctors from various disciplines in order to provide them a holistic overview of his medical status. But he also can restrict the access in a way that every doctor can only see the data that was generated for his discipline.

4.6 Telemedicine center

The telemedical infrastructure can be extended with the modular Tele-Service-Center. User interfaces are used to display patient data on a smartphone or Personal Computer (PC). Medical specialists are able to send messages, call, write E-Mail and send short message service (SMS) to patients in order to give feedback and transmit instructions. A lot of patients can be observed by a group of specialists in the telemedicine center. In case of abnormalities, these medical specialists are able to give direct feedback to a specific patient. Feedback like questions, instructions or advices can be transmitted via a internal message system, E-Mail, SMS or a telephone call. To support the Service-Center automated intelligent data analysis can be implemented and activated as a module for the different diseases.

4.7 Communication infrastructure

The communication architecture is one of the most important parts of the system. Supporting the treatment of different diseases with sensors and actuators in one system imposes a wide spectrum of possible communication needs. To meet these needs, the combination of a basic communication service with a live communication module is used. Like it is suggested in Bluetooth HDP and IEEE 11073 for near field communication [112, 27], we propose to use the basic communication service for normal data transmission and secured data transmission from the data acquisition unit to the central servers. In addition to this, a module for push notifications is attached to the communication service in order to provide the possibility for bidirectional communication at all time (see section 4.7.3).

The communication architecture was implemented in Java with the usage of different frameworks like Hibernate for the database connection and Restlet [114] for the web-service connection. The data storage was realized with an Oracle™ database to provide high flexibility and scalability.

For sensor data transmission two different transmission types were developed and implemented. One transmission type was implemented for the transmission of stored data up to several MB and one type for the live transfer of vital parameters. The usage of these transmission types can be changed by the needs of the users of the infrastructure at any time. Due to push notifications it is possible to store the data on the smartphone for some time and save energy, while still being able to activate the live transfer of the data on-the-fly and get the newest values of the patient on demand. The analysis of the different WAN communication networks like EDGE, UMTS, WiFi in combination with DSL (cf. chapter 4.9), showed, that these networks are capable of transmissions with enough bandwidth to provide a live data transfer, but in a wireless controlled network it is important to keep in mind, that these network are more instable then local network connections [11].

4.7.1 Basic communication service

The basic communication service (figure 4.17) provides a robust and secure data transmission service. For this purpose, we propose a HyperText Transfer Protocol Secure (HTTPS) based web-service (see section 2.1.3.1). Since the Web Service is a very common technique for communication in distributed systems, programming libraries are available for every common programming language [115]. Since HyperText Transfer Protocol (HTTP) is used all over the Internet, in general it can be used unrestricted in nearly every network with Internet access like home WiFi with DSL, GPRS, EDGE, UMTS and high speed packet access (HSPA). Other protocols may be restricted by the provider or a firewall. Therefore a HTTP based Web Service with SSL encryption offers great interoperability and robust communication which can always be used even as a fallback if other communications might fail. The

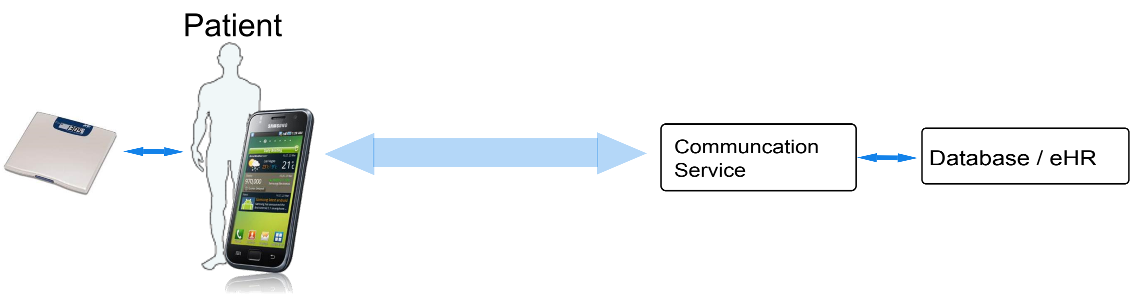


Figure 4.17: The basic communication service is providing a solid and secure data transportation between the data acquisition unit at the patient's side and the central infrastructure. The data acquisition unit is collecting the sensor data via local communication. The communication service is connected to the central database for data storage.

basic communication service is used for all general communication with the central servers, like authentication, request of up to date information of treatment parameters, periodic uploading of sensor data and so on. The central servers offer these different functions though a HTTPS server and the clients can use them with the appropriate HTTPS client software. For each function usage, the client initiates a connection to the server. After authentication, the client can send payload data like sensor data or request information from the server like new treatment parameters. This type of communication is optimized for transferring bundled information such as bundled sensor data of the size of several megabytes. Furthermore, the usages of HTTPS based traffic is a good fallback, since it is accepted in most firewalls while other traffic might be prohibited.

Using the HTTPS protocol imposes protocol overhead for example due to handshakes. For bundled transmission, this overhead can be neglected, but for fast repeated transmission like single value every second or even faster this overhead adds a delay for every transmission and therefore slows down the communication. With the increased round trip times in mobile communication networks the communication performance of a protocol like HTTPS is not suitable for fast repeated transmissions of single values [11]. For this purpose, the live proxy module extends the functionality of the communication service with another communication protocol.

4.7.2 Live proxy module

The live proxy module extends the functionality of the basic communication service. It provides bidirectional stream-based communication (see figure 4.18). The data acquisition unit is connected to a sensor or actuator and initiates a persistent stream connection to the module. Multiple clients can be connected to the proxy module for viewing or controlling the sensor or actuator. The proxy module takes care of forwarding the data coming from the data acquisition unit to the clients and storing the information in the database as well as forwarding the control commands from the clients to the data acquisition unit. Since the data acquisition unit and also the live clients are often located behind firewalls or NAT routers the options for a direct connection between these endpoints are often restricted. For both sides, it is possible to establish outgoing connection, but it is often not possible to offer robust services for incoming traffic. Methods like UDP hole punching (see section 2.1.3.2) offer the possibility to establish a direct connection for data transfer between both sides, if both sides can be instructed via an already established communication [31]. Another possibility is the usage of a central server, that can be addressed from both sides and forward the information to the other side, like a proxy. We propose usage of a live proxy module to establish a fast connection between the patient device and the remote physician. The proxy module opens a server and data acquisition unit and live clients initiate a connection. The authentication for both sides is facilitated by tokens, that can be requested via the web service of the basic communication service, where all authentication is handled. The proxy module sorts the corresponding connections into a session and takes care of storing and forwarding the data. This way, a robust end-to-end communication can be established in every situation. Other advantages are, that the medical data is automatically stored in the central database and can be used for further analysis. With this proxy module it

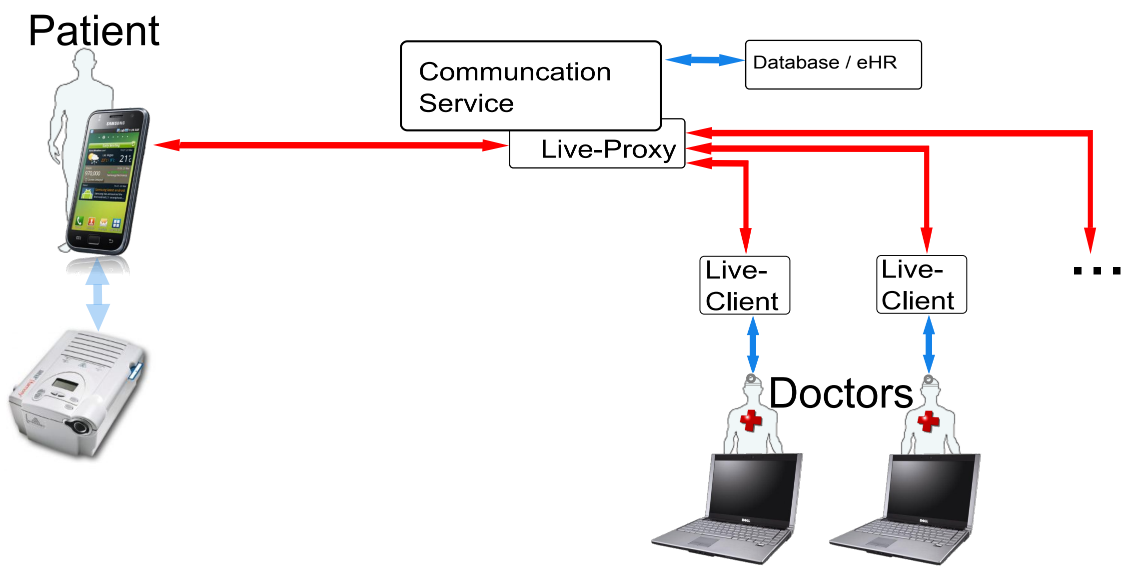


Figure 4.18: The live proxy module extends the functionality of the basic communication service. It provides a bidirectional real-time connection between the data acquisition unit, which is connected to sensors or actuators, and multiple physicians.

is also possible to connect multiple live client to a session because the proxy module takes care of multiplexing the information.

The live client is integrated in the web interface of the telemedical work place. For remote operation of devices, Java applets which initiate active connections to the proxy module, were chosen. This is done, because persistent connections offer more performance than pulling the data via Asynchronous JavaScript and XML (AJAX). Our tests showed the best performance in Java applets for the purpose of a live client operating the remote device. An example can be seen in figure 4.19.

4.7.3 Push service

For now, every communication between the data acquisition unit on the patient's side and the communication service is initiated by the data acquisition unit. Since we want to achieve a bidirectional communication at all time, we integrated a push module as an extension to the communication service. Different possibilities for pushing alerts to a mobile client are possible [116, 117, 118]. The usage of SMS or telephone calls is generating additional costs for the system and especially the time of the arrival of an SMS is not deterministic and depends on the usage of the cellular network. With the recent advances in cellular telecommunication networks and wireless home networks the usage of Internet based solutions offers the most flexible configuration. Consumer electronic devices are designed to be always online. We propose to use a persistent connection like the internet message access protocol (IMAP) protocol with the IDLE command [119, 120].

Figure 4.19: Lower part the telemedical work place showing the integration of the Java applet for remote operation of a flow generator.

For the realization of the push module, a service is offered by the communication server. The mobile data acquisition units can connect to this service and authenticate. The authentication inside the push module is again handled via a token, that can be requested through the basic communication service. When the client is authenticated, it can issue the IDLE command. The service will acknowledge the command and both sides enter the IDLE state. In this state the connection is continued while the client can either end the IDLE state or refresh it. The server can only send alerts in this state. The server has a connection timeout of 30 minutes if no command has been issued in this time, the server will assume, that the connection is lost. To avoid this the client is supposed to refresh the IDLE state at least every 29 minutes.
In addition to the persistent connection we implemented several fallback mechanisms. The mobile device also opens a server, where it can be addressed and triggers can be called. If the persistent connection breaks, the central infrastructure can reconnect to the device if immediate actions are necessary. When the device connects to a network, it checks the status of its global connectivity. If the device has a global internet protocol (IP) address, this IP address is transferred to the central infrastructure. Normally the devices will be located behind NAT routers and only have a local IP address which is not reachable for the central infrastructure. If the local network offers Universal Plug and Play (UPNP) capabilities, a port forwarding on the router is activated and this information is transferred to the central infrastructure. With this information and the active port forwarding connections can be established [121]. Further the integration of Internet Protocol Version 6 (IPv6) and the mobility support of IPv6 offers enhanced connectivity where the mobile device can be reached by the central infrastructure [122]. With this combination of a persistent connection, UPNP and IPv6 technologies a redundant bidirectional communication can be established.
This push module can be used to trigger actions on the data acquisition unit at all times and therefore enable bidirectional communication. Common actions, that will be triggered are an additional measure of vital parameters, transmission of data, a change of configuration or a live data transmission.

4.8 Live communication

The live communication module is especially required in the intensive care support scenario (see 4.2.3). It is used to connect the medical personnel at the support requesting hospital and the experts via real-time audio and video channels. The communication can also be used to contact patients and perform a medical round by video-telephony.

4.8.1 WebRTC

As the live communication is part of the support module, it also has to be platform independent. Regular video conferencing solutions need platform specific software because the usage of the media devices, like microphones or cameras, is restricted by the operating system. This problem is addressed by the emerging Web Real-Time Communication (WebRTC) technology [123]. WebRTC uses HTML5 commands to access the media devices directly inside the browser. This enables us to develop a real-time video and audio communication component that runs completely in a browser. The necessary API calls are not supported by every available browser yet. An overview of the current WebRTC support of the different browsers can be seen at [124]. Figure 4.20 shows the implementation of the video conferencing used in the intensive care scenario where an external hospital with a mobile device (left side) requests help from the experts at the telemedicine center (right side).

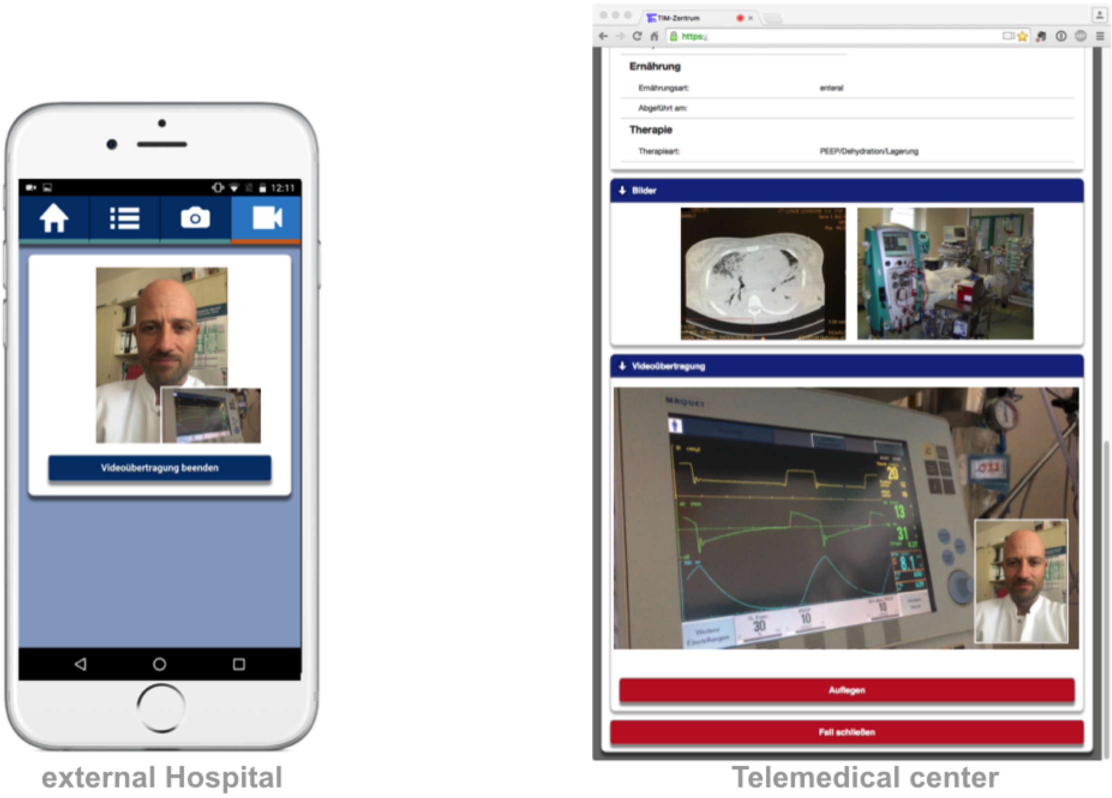


Figure 4.20: Video conferencing between requesting hospital and experts in the telemedicine center

4.8.2 Signaling

The live communication module needs a central server with a fixed address for the signaling process. The signaling process is the communication between the two client applications and is needed for finding a route through the Internet to the other device, negotiate the protocol for video and audio communication, encryption parameters and others. We set up a simple signaling server in Python that communicates via secured web-sockets with the clients. The signaling server is also used for transferring the data and images between the clients and keeps track about the state of the links so that the clients can be informed when a link is closed or broken.

4.8.3 STUN / TURN / ICE

As the communication partners often reside behind a NAT or a firewall the system can't establish a direct connection between the clients [125]. A NAT or firewall hides the private address of clients in a local area network (LAN) behind a single public address. Therefore, the clients can initiate a connection to a remote host but not the other way round. An end-to-end-communication is not possible. Using a Session Traversal Utilities for NAT (STUN) [126] server allows the client to identify its server-reflexive address, which is a combination of the public address of the network and a port. The server-reflexive address is translated by the NAT into the private address of the corresponding client. To establish a connection the client can use a Traversal Using Relays around NAT (TURN) server [127]. TURN is built upon STUN. A TURN server is publicly reachable in the Internet. The client establishes a connection to the TURN server and asks the server to allocate a public address and port. This so-called relayed address can be used by an other client to establish a connection. The connection then has to be relayed by the TURN server for the complete session. To combine and simplify the process of choosing the right method and establish a connection the Interactive Connectivity Establishment (ICE) [128] framework can be used. It gathers all possible connection methods in so called candidates. The candidates are ordered by priority and connectivity. Candidates are exchanged via the Session Description Protocol (SDP) between the clients. Figure 4.21 shows the different communication links for the peers. Both peers connect to the signaling server for exchange of connection parameters. Both peers are behind a NAT or firewall and have to use STUN servers to get their server-reflexive address or TURN servers to relay their communication.

4.8.3.1 Audio, Video and DataChannel

The WebRTC standard defines different communication channels. As soon as a connection is established, channels can be opened or closed by attaching streams to the connection. Video and audio channels need a description of the used codec, bitrates and other parameters that are transmitted to the other peer. Opening or closing channels create events that can be interpreted by the software using the WebRTC framework to react and attaching the own stream for bidirectional communication for example. WebRTC also supports DataChannels that can be used to transfer data directly between the peers. It is possible to add or remove channels from an existing connection via the renegotiation function. After changing the connection parameters (e.g. by adding a DataChannel) the connection is renegotiated and the framework opens the added channels or closes unneeded ones. In our application we first used DataChannels for the transmission of the patients data and images but due to shifting design goals we implemented the data transmission into the signaling server. This allows us to expand the system and synchronize the information

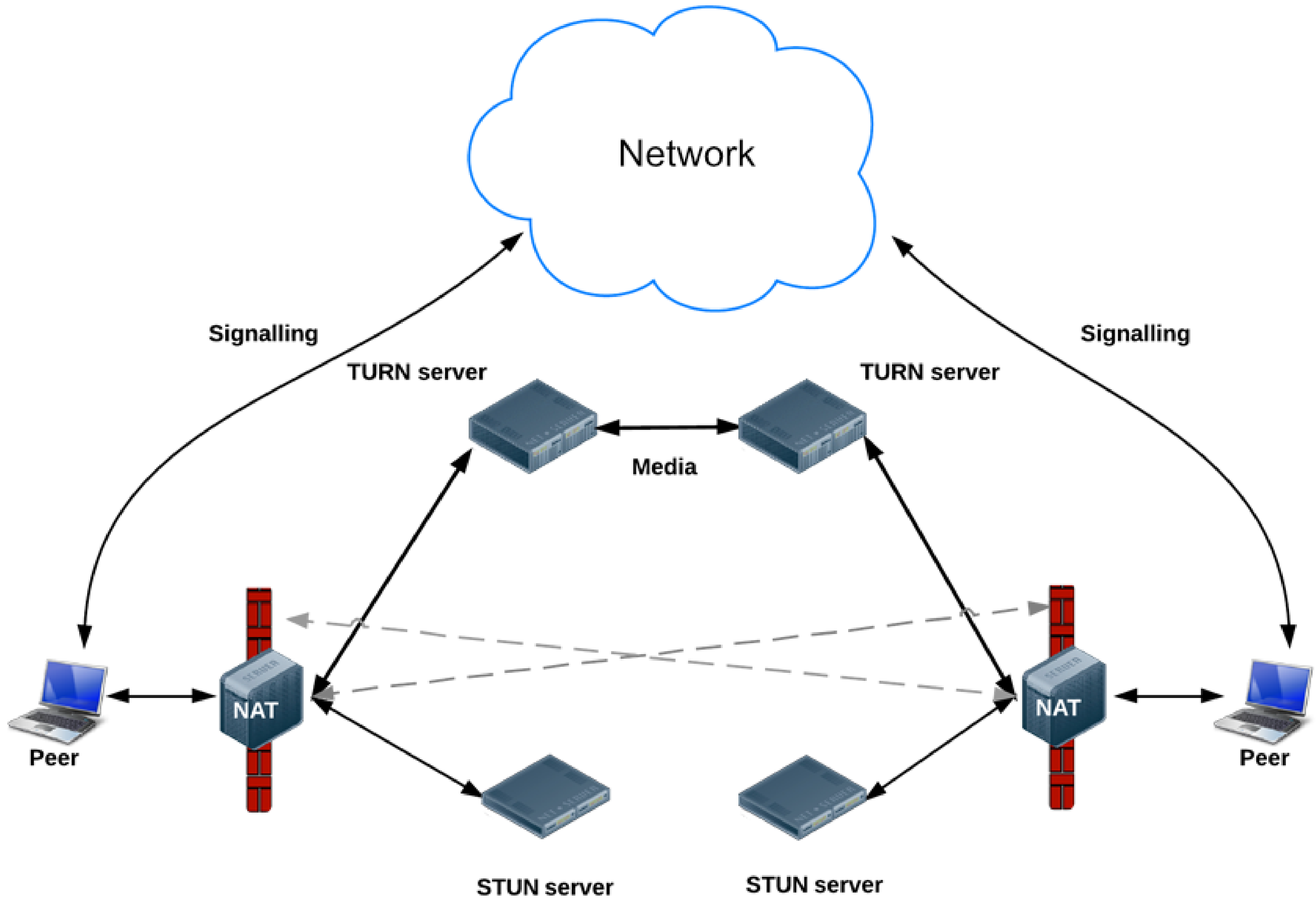


Figure 4.21: Different methods for connecting two peers behind a NAT or firewall (ICE framework). Image from [129]

between multiple expert teams that are connected to the signaling server. The interface for transferring patient data is depicted in figure 4.22 while figure 4.23 shows the interfaces for transferring images from the requesting hospital to the experts at the telemedical center.

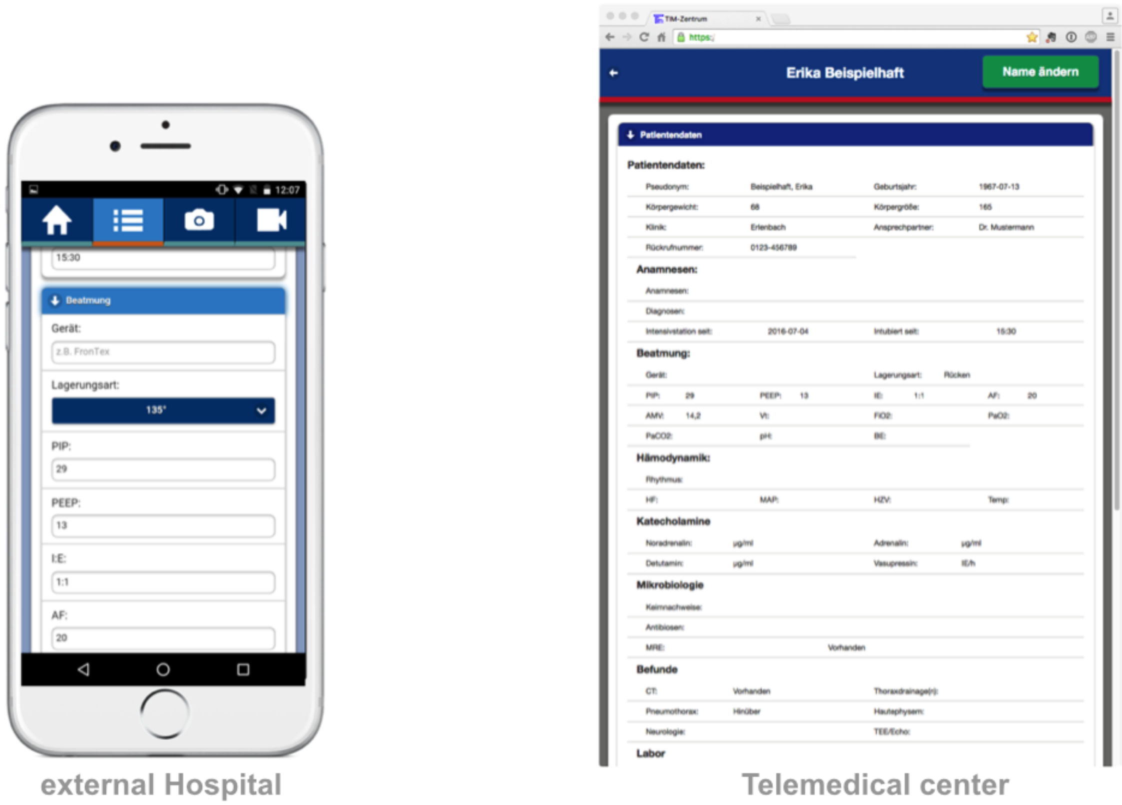


Figure 4.22: Transmission of patient data to the experts in the telemedicine center

4.8.3.2 Encryption

In the telemedical context data security and privacy have a very high priority as we transfer sensible data. The WebRTC framework allows no unsecured connections. Every communication channel is encrypted by default. Figure 4.24 shows how the complete application can be secured. The audio and video channels are encrypted with the Secure Real-time Transport Protocol (SRTP) while DataChannels are secured via Datagram Transport Layer Security (DTLS). The connection to the signaling server isn't encrypted by default as it is not part of the WebRTC framework. We use secured web-sockets for the communication to the signaling server. The websites containing the client applications are delivered via HTTPS only. This ensures that every information that is exchanged between the client is properly secured.

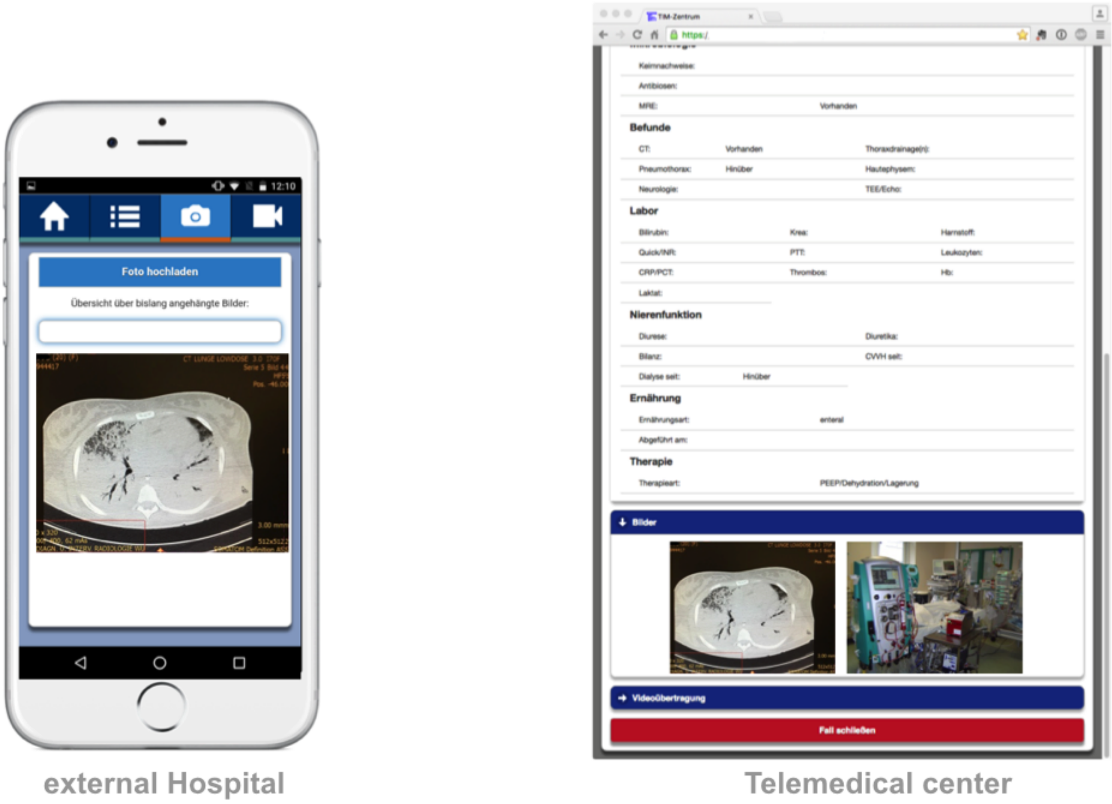


Figure 4.23: A requesting hospital sends images to the experts in the telemedicine center

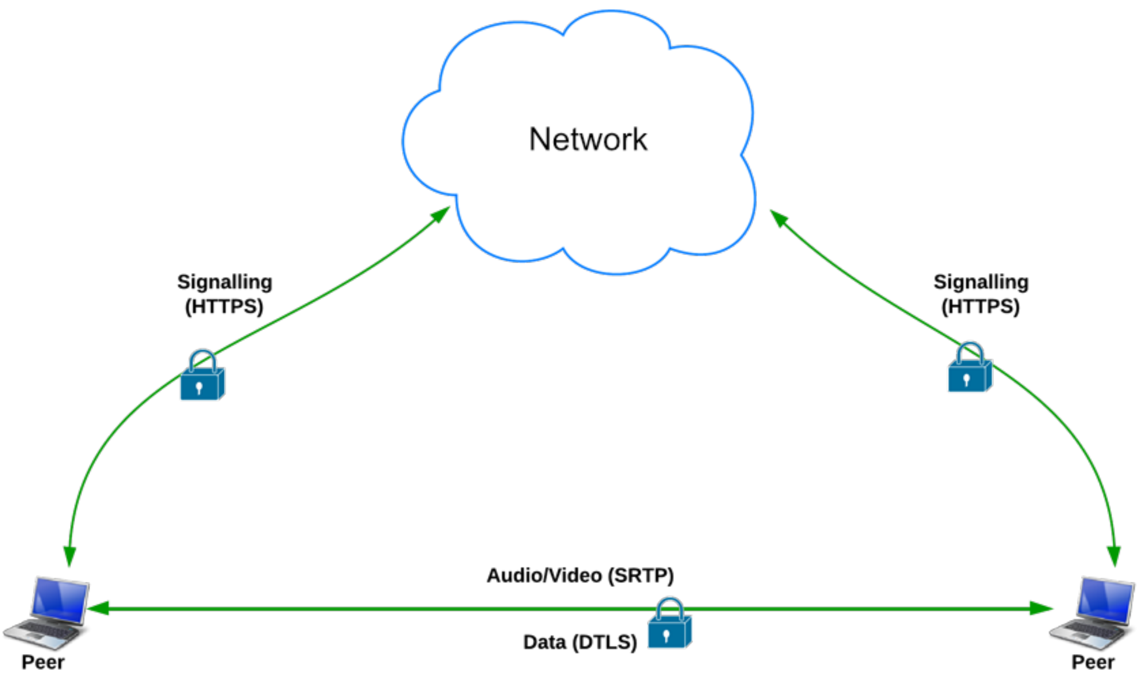


Figure 4.24: Securing the pathways for WebRTC communication. Image from [129]

4.8.3.3 Privacy

Data transmissions of patient data do not contain names or birthdays of the patients to further protect the patients privacy. The patients age is transmitted as it is a crucial information for the experts. All the patients data is stored under a pseudonym to identify and merge different data transmissions. If the patient is transferred to the other hospital the pseudonymized data can be attached to his information in the clinic information system.

4.9 Link Characteristics

While we were designing our telemedical system and collected the requirements we thought about the different communication links that connect the different components of the system (see figure 4.25). The last section listed the possible technologies for the different types of communication links. But we wanted to know which specific technologies are suitable for our kind of application. Therefore we performed some tests with different communication technologies to verify if they are suitable for the designed tasks. The tests gave us a good overview for the possibilities of the different connection types. Using a mobile communication network like GPRS,

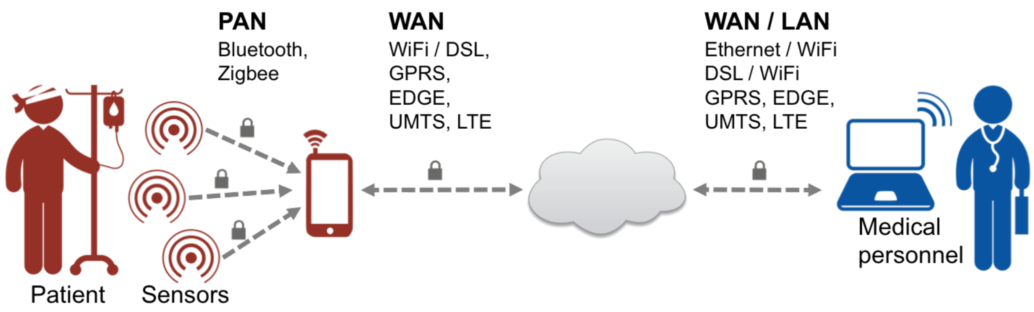


Figure 4.25: Communication links used for the telemedical system

EDGE, UMTS, HSPA or LTE to transfer signals from a device to a controller brings new challenging aspects for researchers. Compared to conventional networks the use of mobile communication networks may cause:

- longer transmission times (delay)
- variation of transmission times
- higher packet loss
- changed packet reception order

These aspects may lead to reduced performance and instability of the entire system. Therefore, an analysis of the link characteristics of the used communication link is needed to design a optimized and stable system that is adapted to the link characteristics.

In general, the faster the network operates, the smaller the effect of time delays will be. The analysis and co-simulation of an IEEE 802.11B communication system in [130] showed, that data rates less than 11 mega bit per second (Mbps) lead to significant performance degradation. They also came to the conclusion that the data transmitted over the communication network should be prioritized to assure an optimal performance.

4.9.1 Test set-up

For the comparison of the different network types and the influences of using a smartphone instead of a computer, we use the measurement of the RTT of packets to determine the characteristics of the different networks. Since the wide area networks have asynchronous bandwidth for the downlink and the uplink further characterizing of the different network types can be done by using the one way delay like it was done by [32] for UMTS networks. The RTT gives a very good approximation of the different link characteristics. For control in telemedical application transmissions in both directions would be needed.

In addition to the RTT, the jitter and the percentage of lost packets are used to evaluate the link characteristic (see 2.1.4.3). The jitter is defined as the variance of the RTT and is a very important value for characterizing networks because it describes the determinability of the arrival of a packet [131].

In the tests UDP packets were used to reduce the protocol overhead in the test scenarios. A server was set up, that was listening on a defined UDP port for packets. After receiving a packet from a client the server sends the whole packet back to the client. In this case the computing time T_C is very small and is negligible in this context. The client is sending a random packet to the defined port of the server and afterwards waiting for reception of the same packet. The client is measuring the time between sending the first bit to the server and receiving the last bit of the packet from the server. The server was implemented in Java. For wide area network tests it ran on a virtual server in a data center in Germany while the server for the local area network tests was realized on a normal PC with a Gigabit Ethernet connection. The client is implemented in Java and runs on a PC or Android phone. The tests for this work were done in a small city near Würzburg. The virtual server for the Internet tests was located near Berlin. This corresponds to a linear distance of about 390 km which is a normal distance for wide area connection. For the smartphone tests a Samsung Galaxy S I9000 running Android 2.3.3 was used with O2 as the mobile network provider. Figure 4.26 shows the entire setup for the tests. All tests were done for different packet sizes from 1 byte up to 65507 byte, for each packet size 100 test runs were done to calculate the mean RTT, the jitter and packet loss. Table 4.7 shows the maximum theoretical bandwidth for the uplink and downlink of the different transmission techniques that were used for the tests. Some of the transmission techniques were used in combination, like WiFi for the connection to the local network together with a DSL 16000 line for the connection to the Internet In those cases with a combination of different transmission techniques the bandwidth

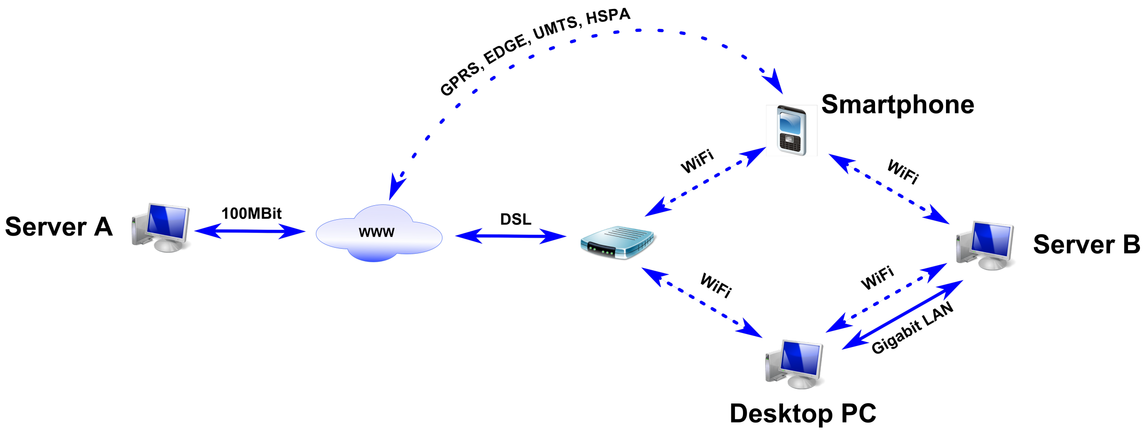


Figure 4.26: Overview of the complete test setup

corresponds to the lowest available bandwidth.

Table 4.7: Maximum theoretical uplink and downlink bandwidth of the different transmission techniques

	Downlink	Uplink
GPRS	56.6 kbit/s	13.4 kbit/s
EDGE	236.8 kbit/s	118.4 kbit/s
UMTS	384 kbit/s	384 kbit/s
HSPA	14.4 Mbit/s	5.76 Mbit/s
LTE	300 Mbit/s	75 Mbit/s
DSL 2000	2048 kbit/s	192 kbit/s
DSL 16000	16.000 kbit/s	1.024 kbit/s
WiFi IEEE 802.11n	600 Mbit/s	600 Mbit/s
Gigabit Ethernet	1000 Mbit/s	1000 Mbit/s

4.9.2 Test Results

In network system, the components are usually connected via a very fast network connection. For comparison the first tests were done with and direct connections via Gigabit Ethernet and also a localhost connection of one PC. The results are shown in figure 4.27. Due to the fast and stable network these connections have a very small RTT and jitter and have no packet loss. This gives a feeling of how normal communication channels used for critical applications behave. The figure shows that the RTT increases linear with the increasing packet size.

In figure 4.28 the communication characteristics for wireless communication in the local network are shown for a PC and a smartphone. For these tests, the server was set up in the local network and connected via Gigabit Ethernet to the network. The clients, a PC and a smartphone, were connected via WiFi to the local network.

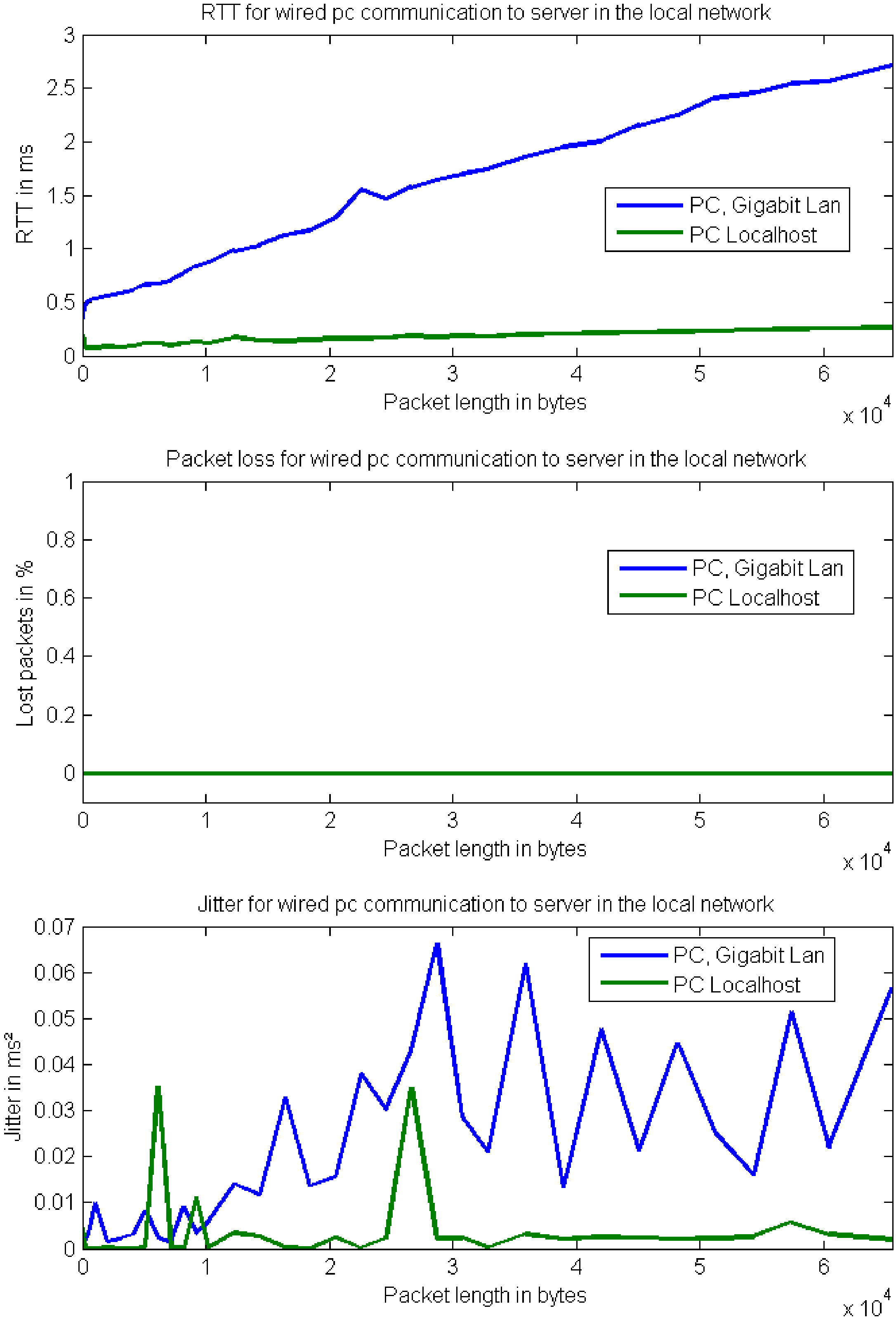


Figure 4.27: RTT, packet loss, jitter for wired communication to server in the local network of a PC and lost host communication.

The RTT for the PC and smartphone communication via WiFi are very similar, but the smartphone produces a higher packet loss. The jitter was quite similar for both communication devices. In figure 4.29 the RTT, jitter and packet loss is shown for the communication to a server in the Internet from a local network via two different DSL lines for a PC and an Android smartphone. The smartphone and the PC were connected to the local network via WiFi. The local network was connected to the Internet via the DSL line. For comparison the tests were also done with the PC connected via wired Gigabit Ethernet to the local network for one DSL line. The RTT of the slower DSL line (DSL 2000) is of course higher for the PC as well as for the smartphone. In comparison the smartphone has a higher RTT for both DSL lines than the PC. In addition to this the jitter and packet loss of the smartphone is a little bit higher compared to the PC. The figure shows that for the connection the packet loss is quite small until the packet size is bigger than a connection specific size. Then the packet loss goes up to 100%. Of course for the tests with 100% packet loss no RTT or jitter can be computed.

Caused by the higher bandwidth of WiFi connections than DSL lines the RTT of local area connections, like they were shown in figure 4.28, is smaller than the RTT's for wide area connections shown in figure 4.29. Also the jitter of the local area connections is smaller than the jitter of wide area connections. The packet loss rate of connections in the local network via WiFi and connection in wide area networks via WiFi are very similar, this means that the DSL lines causes only very few numbers of packet loss. Figure 4.30 shows the link characteristics for mobile communication of the smartphone via EDGE and HSPA. EDGE is an extension of the GPRS standard for mobile telecommunication while HSPA is the extension of the UMTS standard [132]. Due to the higher bandwidth of HSPA the RTT is shorter there than it is in the EDGE network. The packet loss rate for the EDGE communication is also higher than for the HSPA communication, but the jitter of the EDGE communication is a little bit smaller than the jitter in the HSPA communication. The comparison of figure 4.29 and figure 4.30 shows that the RTT of the EDGE communication is higher than the RTT of the communication via WiFi combined with DSL 2000. The RTT for the communication via HSPA is between the communication via WiFi combined with DSL 2000 and WiFi combined with DSL 16000. This is mainly caused by the imposed bandwidth of the different connections. The comparison of the two figures also shows, that the packet loss and jitter of the mobile communication is higher than communication via WiFi combined with DSL. Comparing figure 4.30 with figure 4.28 and figure 4.27 shows that mobile wide area communication imposes higher RTT, jitter and packet loss than local area network communication.

4.9.3 Test Summary

Conventional time critical applications only use localhost connections or local network connections and therefore have a very small RTT and jitter as well as no packet loss. Figure 4.31 shows the result of all test setups used. This shows using wireless

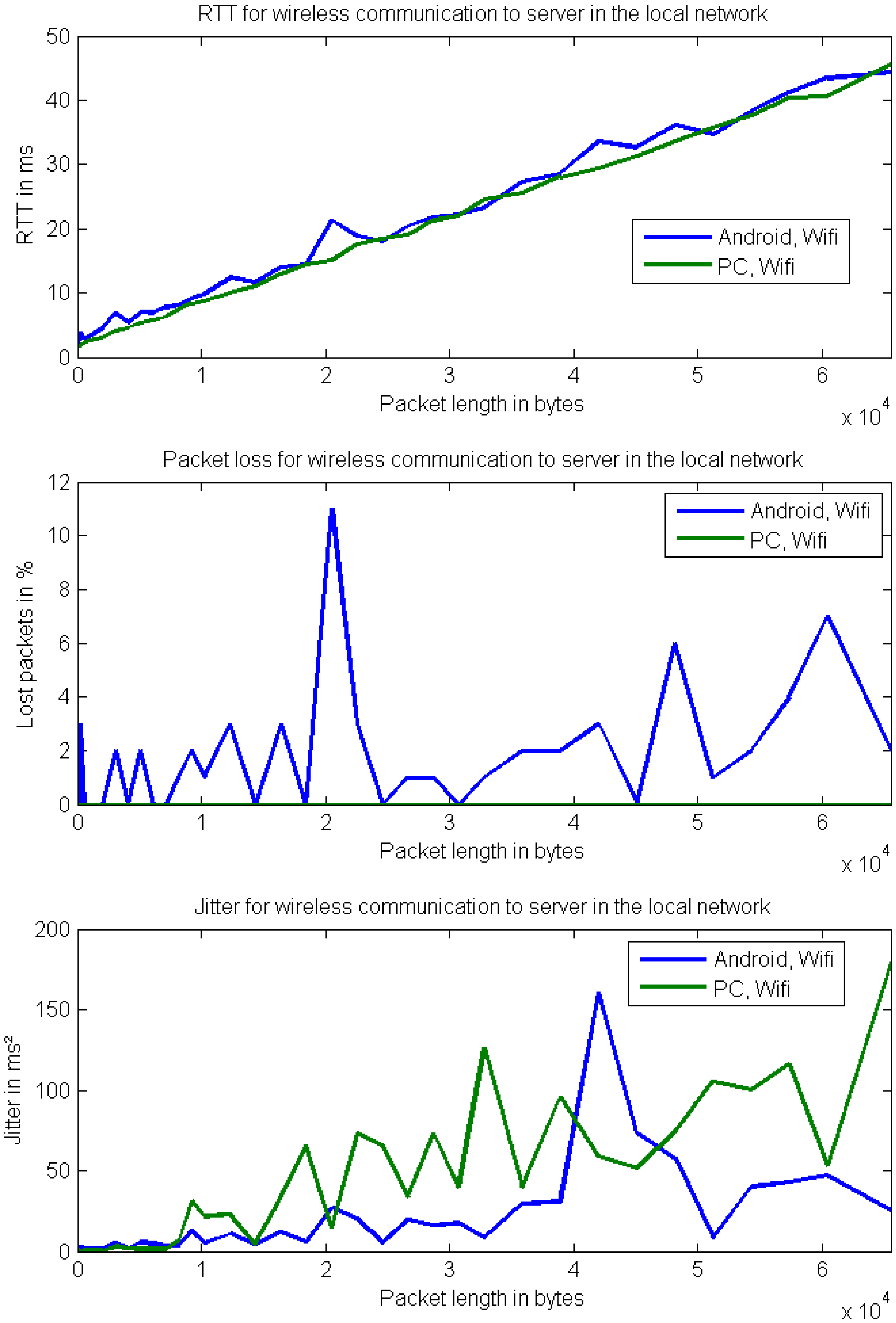


Figure 4.28: RTT, packet loss, jitter for wireless communication to server in the local network for smartphone and PC.

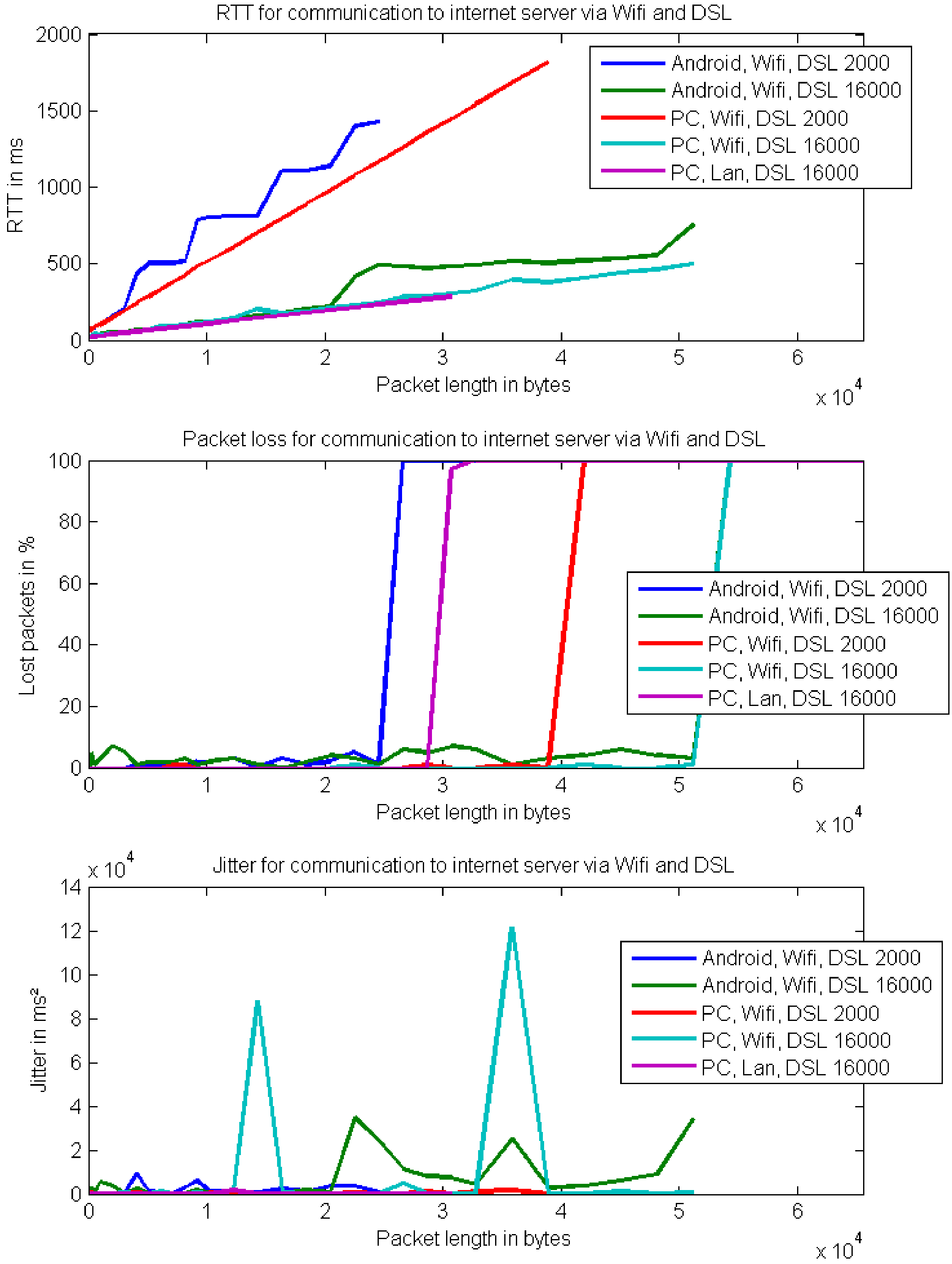


Figure 4.29: RTT, packet loss, jitter for communication to Internet server via WiFi and DSL for smartphone and PC.

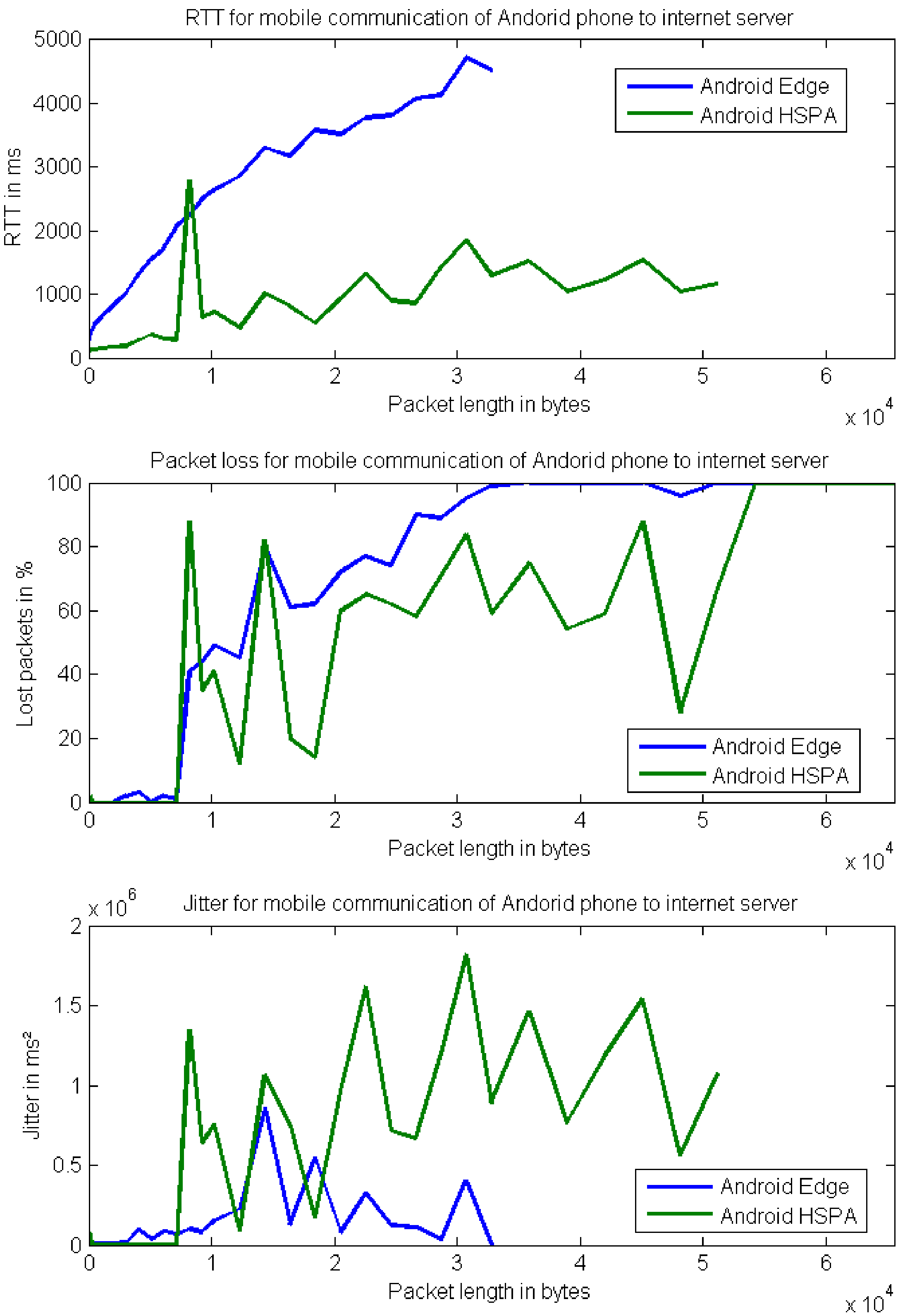


Figure 4.30: RTT, packet loss, jitter for mobile communication of Android phone to Internet server.

communication even in the local network leads to higher RTTs, jitter and packet loss. Wide area connection and mobile connection have even higher RTTs, jitter and packet loss. This is very important and must be kept in mind when designing applications over wide area network and mobile communication links. Another very

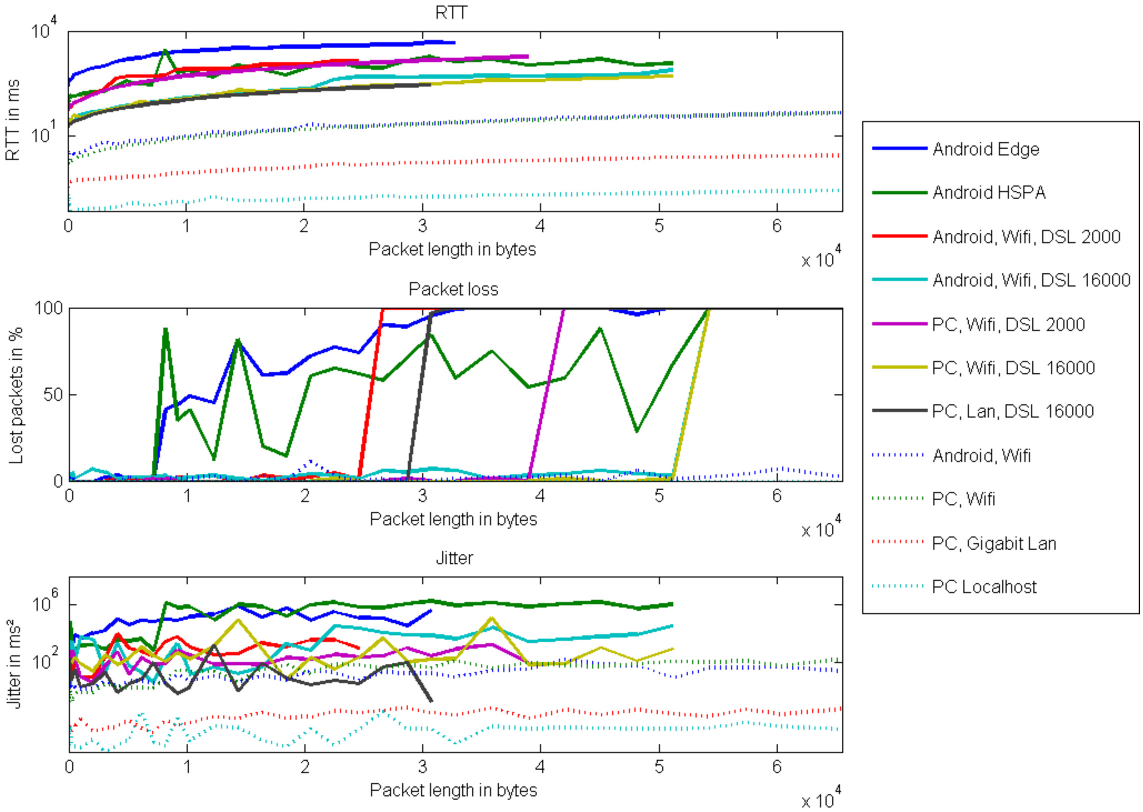


Figure 4.31: RTT, packet loss and jitter for all used connections. The RTT and jitter are plotted with a logarithmic scale for the y-axis.

interesting result of the tests is, that using a smartphone instead of a standard PC often imposes a higher packet loss. This might be caused by the miniaturization of the chips and antennas and the resulting interferences between the components. This miniaturization is necessary to integrate all the common features like WiFi, Global Positioning System (GPS), GSM, UMTS and so on in the very limited amount of space in a smartphone.

The tests showed, that using wireless and mobile communication networks especially with smartphones impose different aspects like higher RTT, higher jitter and more packet loss. It is very important to think about the consequences of this aspects when designing a networking system over wireless and mobile communication networks. The different layers of the ISO/OSI model need to be adapted to reduce the consequences of this aspects. For example the higher jitter and packet loss imposes undetermined packet arrivals while for time critical application regular packet arrivals are very important. In the worst case this aspect leads to lost packets and packets arriving in the wrong order. When using Transmission Control Protocol

(TCP) connections this leads to packet retransmissions. On the one hand this is good because it is assured that the packets arrive at the target, but on the other hand this leads to higher transmission times and waiting packets when a retransmission is triggered. These are two very big disadvantages of TCP. If the transmission time is important, it might be better to use UDP and take care of missing packets or the ordering of packets in an upper layer. Hereby the highest transmission rates can be achieved. Figure 4.32 shows the comparison between TCP and UDP communication from another test in a best case scenario through a virtual private network (VPN). It is clearly visible that the TCP connection (light blue) suffers from a much higher delay than the UDP communication. In a worst case scenario (see figure 4.33) the higher delay of TCP connections in comparison to UDP connections is even more visible. Often late packets can be dropped because it is too late to use them for

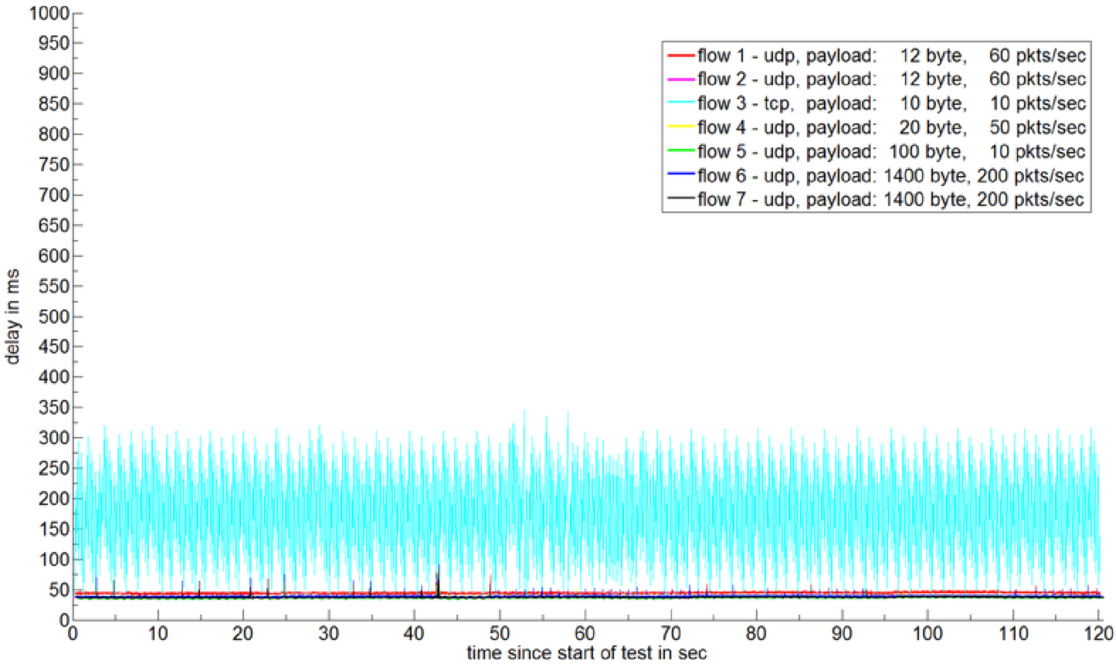


Figure 4.32: UDP and TCP delay (best case)

the computation. This shows that the upper layers of the ISO/OSI model need to be adapted to the needs of the network system. The use cases for our telemedical system are focused on longterm monitoring of patients, asynchronous data transfer and communication. These scenarios can be performed well over the different communication links we evaluated. With some adoptions to changing bandwidth a reliable data transfer can be established and assure the transmission of the patients data while video-telephony uses methods of graceful degradation to adapt for worsening connections. As no critical control applications were implemented the delay effects of the different network types did not affect the functionality of the system.

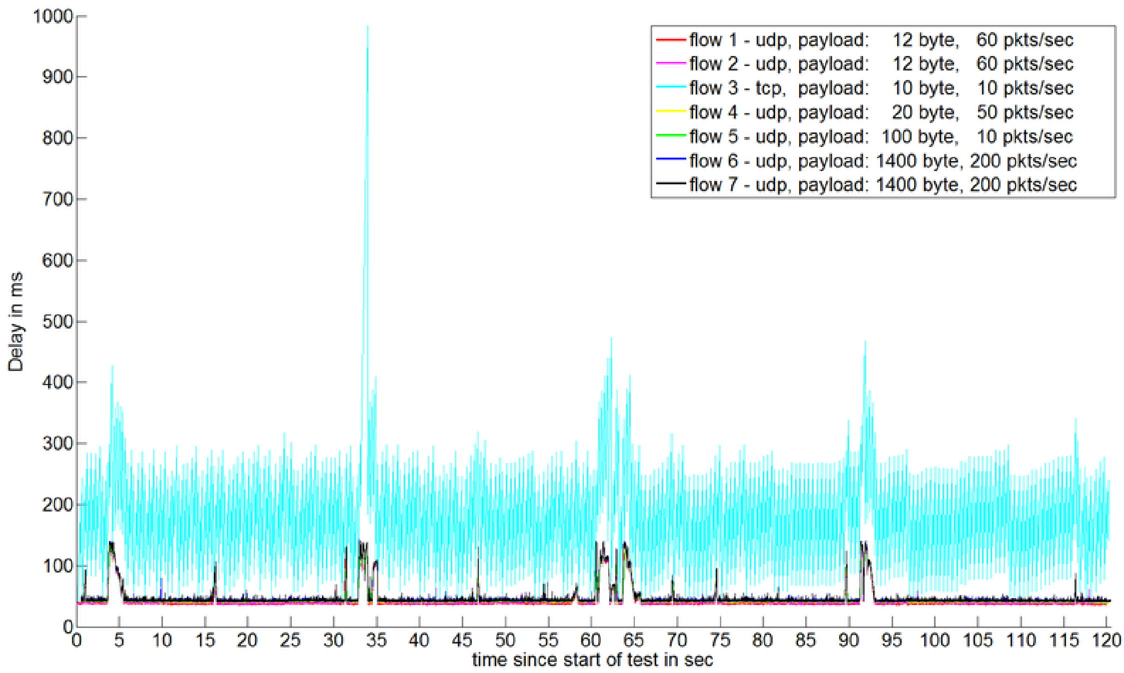


Figure 4.33: Delay of UDP and TCP streams (worst case)

4.10 Summary

This chapter described the design and development of a complete telemedical system that is abstracted from special characteristics of a single use case. Figure 4.34 shows an overview of all the components and modules of the created system. It consists of the patient device, which is represented as a smartphone here, that handles the communication with the medical sensors on the one side and the backend service on the other. The telemedical workplace is the interface where the medical personnel can access the system. Storage and analysis modules take care of archiving and analyzing the data. Several interfaces allow data transfer to other systems or persons for integration with other systems. Additional communication links allow direct communication and data transfer between the patient device and the telemedical workplace without the need of specialized hardware.

Conclusion With our design and implementation we created a complete, generic telemedical system. It showed that it was capable of handling three different use cases that build upon real life scenarios for telemedicine applications. The use cases were strategically chosen (cf. figure 4.2), to get the requirements from edge cases so that cases with lower requirements are subsumed. To our knowledge this is the first telemedical system, that is abstracted from a specific disease and capable of supporting different kind of treatments. We proved that it is possible to combine standard COTS hardware and commercial medical products to form a telemedical system. That lowers technical prerequisites for rolling out such a system into the

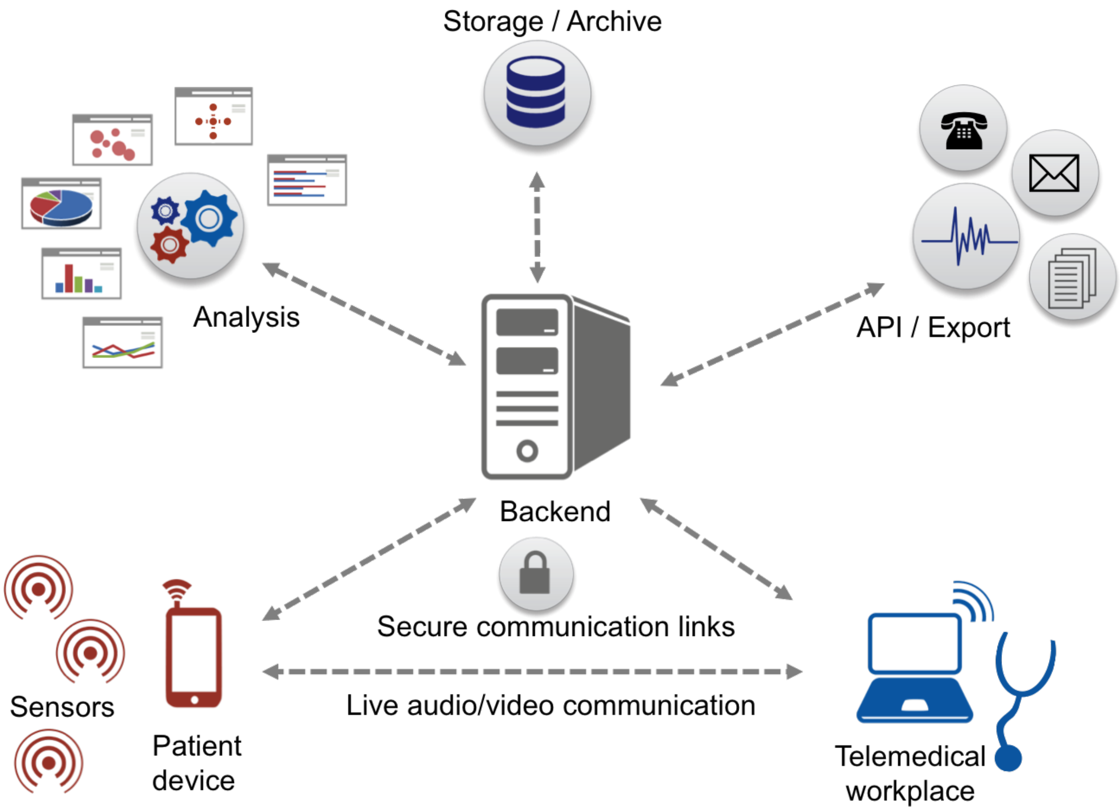


Figure 4.34: Overview of the developed generic telemedical system

daily routine. It also results in low initial investments and reduces the costs for operating such a system. The involvement of all stakeholders in the design phase resulted in a high acceptance and usability of the system. With the live communication modules we could improve the transfer of medical expertise over the distance. The many interfaces to the system allow a fast and easy integration of other systems, sensors or users into the system and expanding the functionalities.

Chapter 5

Extension with a rule-based decision system

After the development of the telemedical system we had wanted to dive deeper into the workflow and address underlaying problems, like the scalability of the system or reducing the workload for the medical personnel. The generic, open and modular design of our system allows an easy integration of new components and extension of the functionality.

5.1 Outline

Telemedical systems offer lots of information about patients to the supervising personnel. The doctors and nurses are in need of methods to filter, analyze and prioritize the large amounts of data. We integrated a powerful rule-based decision system, Telemedical Applications with Rule based Decision- and Information-Systems (TARDIS) [15], into the telemedical system to allow individual filtering, data analysis and alarming for each patient. Especially interesting is the detection of trends in the data of the patients, rapid changes in the health status or the correlation of different parameters.

5.1.1 Motivation

Telemedical systems are developed to cope with the lack of medical personnel and the rising patient numbers. Assuming that the telemedical system is used in the daily routine, it is obvious that there will be a shift in the doctor-to-patient ratio. This means that the telemedical system has to have a high scalability to fulfill that goal. We therefore have to provide techniques to reduce the workload of the medical personnel and keep the possible large amount of patients and the even larger amount of data manageable for the users of the system. According to figure 5.2 the process of knowledge extraction from various data sources needs some processing of the data (see section 2.3). We make use of the domain specific knowledge of the users and let them create their own rules for processing the data. This allows to efficiently extract useful information out of the data. Figure 5.1 gives a basic overview for the rule-based system. The doctors define rules, that are processed on the data that is

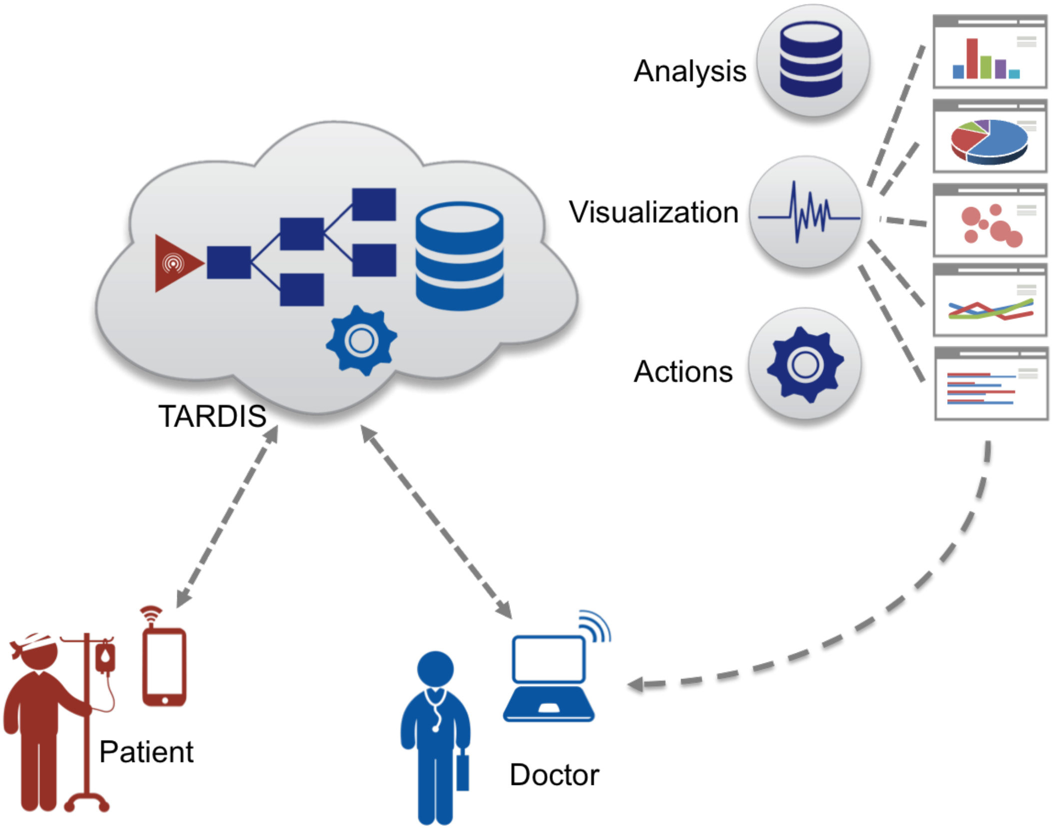


Figure 5.1: Overview Telemedical Applications with Rule based Decision- and Information-Systems (TARDIS)

collected from the patients. According to the rules, the system can generate various visualizations or performing actions to support the medical personnel.

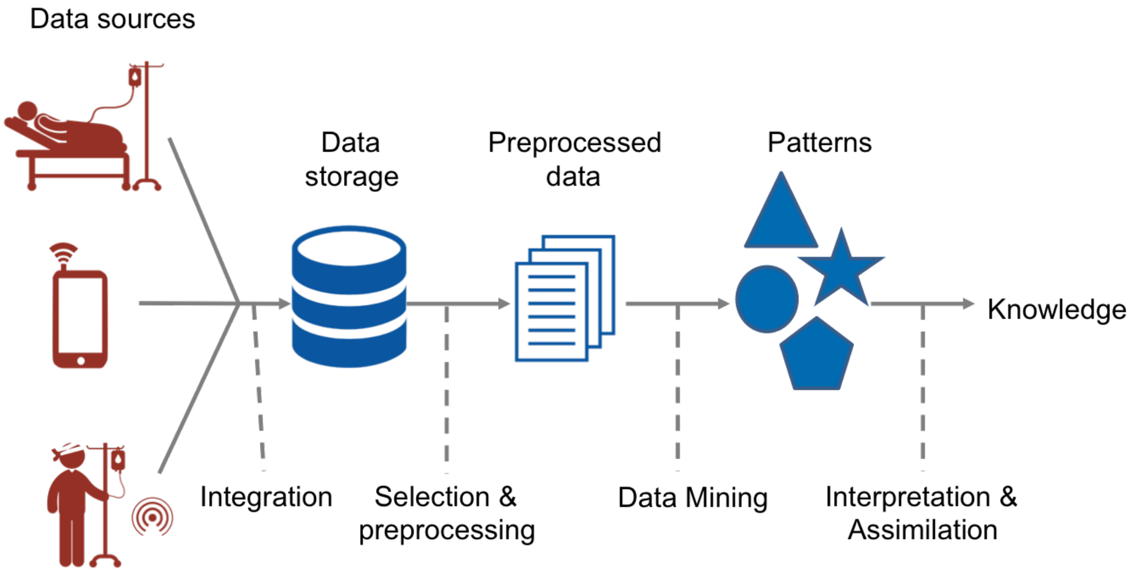


Figure 5.2: The process of knowledge extraction from data sources

5.1.2 Goals

We wanted to add a component to our system that increases the scalability in respect of the patient numbers and the amount of data that has to be analyzed and reviewed by the doctors. Building this on top of a complete telemedical system solves most of the infrastructural problems beforehand but there are still a lot challenges to be mastered. When integrating the rule-based decision system we had the following problems and questions in mind:

- How can we reach a high scalability of telemedical systems?
- How can the workload be reduced for the medical personnel that take care of the patients?
- What are possible features that increase the safety of patients or the medical personnel?
- How has the infrastructure to be designed in order to prepare higher level analysis of the data?
- How should such a system be designed to be efficiently used by non-technical users?
- Can the system give feedback to patients about the progress of the treatment?

5.2 System description

5.2.1 Overview

This system is designed to be as flexible as possible in order to address many various fields of application. Therefore, a modular design is used and the different modules are loosely coupled. It is written in Java to be platform independent and be able to run on desktop computers, servers or mobile devices as well. Figure 5.3 shows an overview of the system that consists of three main modules: the rule solver, action manager and the graphical rule editor. The physician has to review all data

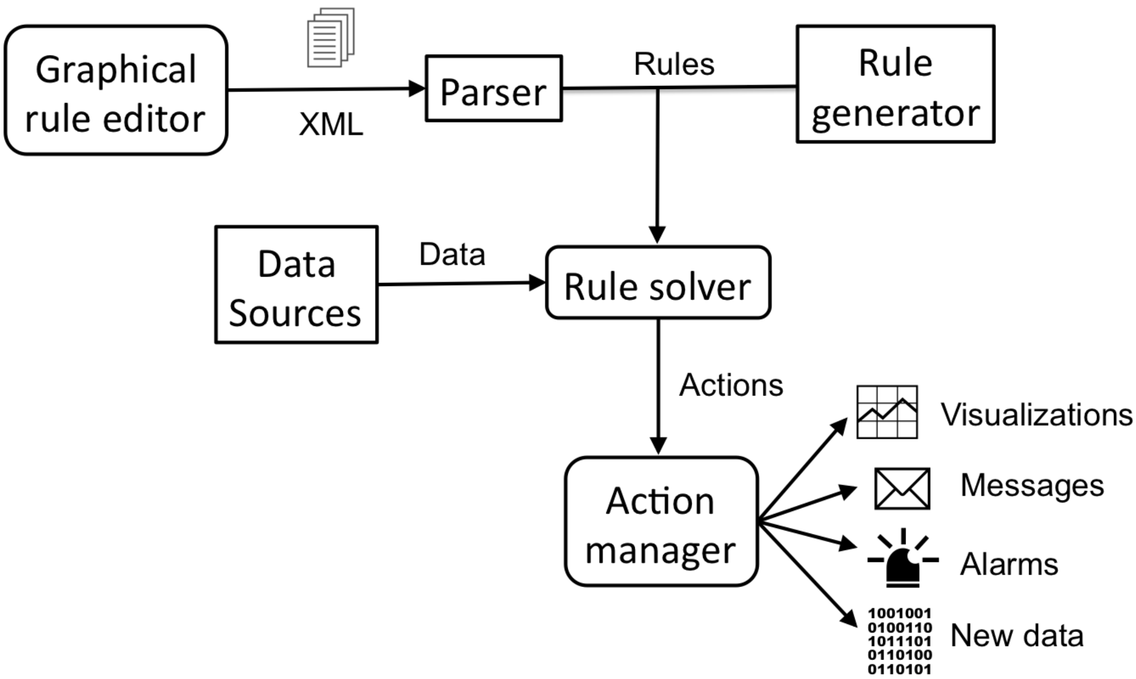


Figure 5.3: Overview of the TARDIS components

collected from the patients in order to evaluate the status of the patient. This produces an enormous workload for the physician. To reduce this load the system provides some mechanisms of intelligent filtering and presentation to the physician. The rule interpretation framework allows the physician to create rules. These rules are applied automatically to incoming data. When a rule fires, various actions can be performed automatically. This enables the physician to create simple filters, like sorting the data by a specific value or design a complex behavior that alerts him via email or text message when some critical values in the patients vital parameters are recorded. Furthermore, additional algorithms have been integrated, for example to detect a desaturation of a patients blood oxygen level and generate a warning. Figure 5.4 shows a simple example of a rule that can be created with this framework. The figure shows how the rule is represented in the graphical rule editor for the physician. It takes two measured values (blood pressure and pulse) and compares them to predefined values. These thresholds can be set individually for each rule. When

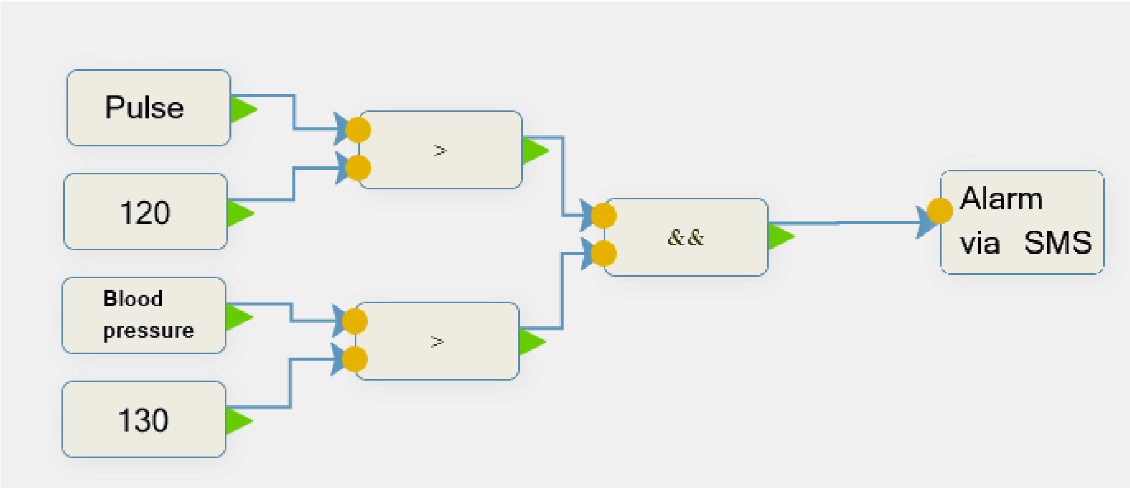


Figure 5.4: An example of a rule that alerts the doctor when some parameters reach critical values. Complex rules can be created by medical personal with this graphical editor by drag-and-drop.

both criteria match an event is generated. In this fictitious example the doctor is alerted via text message when the patients pulse is over 120 while the blood pressure is over 130. In medical scenarios, the data has to be treated differently for every single patient. The disease, health status and other factors change the definition of "healthy" for every person. Threshold values, that are extremely critical for one patient can be absolutely normal for another. The rules are therefore linked with the patient and threshold values or other parameters can and have to be defined for every patient individually.

The framework can handle several input sources, like values stored in a database, constant values or timestamps. It is also able to concatenate rules to form a much more complex behavior. With the implemented set of operators and comparators and the possibility to form concatenated rules, the framework is Turing complete and can therefore do every possible calculation. With each rule, a wide range of events can be triggered. These range from changing values used in other rules over storing information in a database to alerting functions via mail or text message.

5.2.2 Components

5.2.2.1 Graphical rule editor

The graphical rule editor is the user interface used for building up the base of rules that should be resolved by the system. Figure 5.5 shows the graphical rule editor integrated into the telemedical framework. It is realized as a browser application using HyperText Markup Language (HTML), Cascading Style Sheets (CSS) and JavaScript (JS) to be able to run on any platform in order to create and edit the rule base. The exemplary depicted rule would analyze the pulse values and generate a message, that notifies the doctor, when the values are above or below the threshold.

A further description of the different parts in the editor can be found in section 5.2.2.2. The editor has to provide a high usability. The knowledge, that has to be transferred into rules is often held by persons that are non-experts in computer science. The editor provides an intuitive way to design correct rules by showing only valid input sources for the rules and providing a graphical version of the rules that are easy to understand. Every block (see figure 5.5 lower middle section) represents a source for information, a processing rule for the information or an action that is executed when the rule is fulfilled. Every block has different inputs and outputs, depending on its type. The inputs are shown on the left edge of the block, depicted by a small orange circles for each input. Outputs are visualized by small green triangles on the right edge of each block, that can be dragged to another blocks' input to connect the blocks. Connecting the blocks creates an information flow that is visualized to the user by the blocks and the connections between them. This format helps the user to understand easy and quickly which information is processed, which processing functions are used and which reactions are triggered when the right conditions are met. Some input sources contain very much information that may

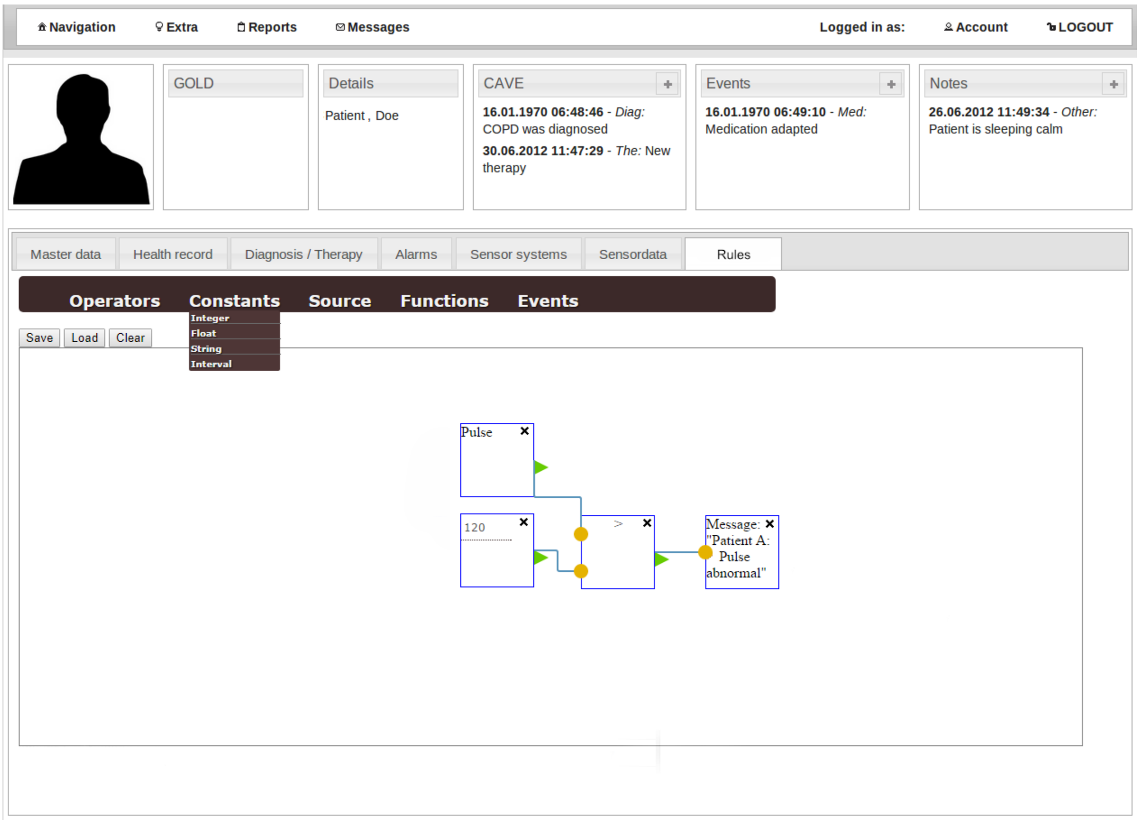


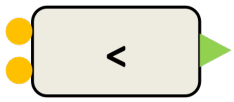
Figure 5.5: Interface of the rule editor in the telemedicine system

have to be pre-filtered to create helpful rules. On the top edge of some blocks are violet circles that can be used to constrain the input source (an example can be seen in figure 5.8). If they are connected to a block that holds information how to constraint the information it is used to select the information that is loaded from the input source. Otherwise all the information that is hold by the input source is loaded. Every time the rules are saved, the editor transforms all rules into a machine-readable XML file that can then be sent to the rule solver, which is responsible for interpreting the rules.

5.2.2.2 Basic of TARDIS functionality

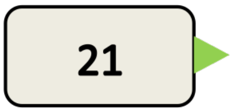
Access to data and essential functionality is provided by TARDIS with several modules, which are presented in this section:

- **Operators:**



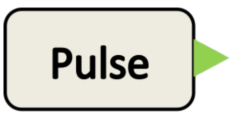
Operators provide the basic functionality of the rule based system. The operator blocks have two inputs (yellow circles on the left side), where constants or data sources can be attached. It is also possible to attach the output of other functions to these inputs. The available operators are the mathematical comparators (“<”, “>”, “<=”, “>=”, “==”) and two functions to concatenate blocks with “and” (“&&”) or “or” (“||”). The inputs are compared with the selected operator and the result is given to the output (green triangle on the right side) as a boolean value (“true” or “false”).

- **Constants:**



Constants blocks come with an input field, where the user can define values by hand. These values cannot be changed by the rule solver and are used to define threshold values or constraints.

- **Data sources:**



The different data sources, like parameters of medical sensors or patient records of other systems, are available as source blocks in the editor. Only sources that are linked with the current patient are shown. Every source block provides an output, that can be connected to an other block to create data flows.

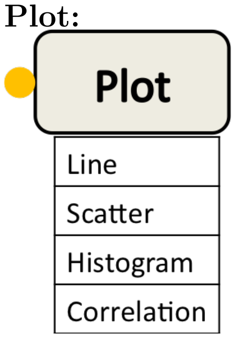
- **Execute:**

When a rule is fulfilled, the system should perform an action. The execute block is able to execute system commands and therefore gives the ability to start other software applications. In this depicted example, it is used to provide the possibility to send an e-mail when a rule is fulfilled. The block is able to create every other reaction that can be performed by executing system commands.

- **Alarm:**

The alarm block creates an alarm event inside the telemedical framework. These events are documented and are shown in the overview of the patients status. Further reactions, that are performed when an alarm is raised, can be configured in the telemedical system itself. An example where this block is used can be seen in figure 5.4.

- **Plot:**



The plot module serves as data drain and therefore has an input able to process several data sets. It is also capable of doing complex visualizations, using the underlaying matplotlib module from Python. The visualization module is further described in section 5.5.1.

While implementing the different use cases, additional features were added. These are described in the context of the respective use case in section 5.4.

5.2.2.3 Rule solver

The rule solver is the inference machine that gets the rules, the input values and checks if the rules are fulfilled. The rules themselves can be divided into two parts: The atomic rules are used for comparison of values while complex rules concatenate two rules with an “and” or “or” condition. This enables the user to form very complex behaviors by combining many different rules. The values, that are compared by the atomic rules, can have the typical data types like integer, floating point values or strings. The interpreter can load the values from many different sources:

- **User input:** Users can define values, e.g. thresholds, by inserting numbers or basic mathematical expressions. These values are static values and cannot be altered by other rules.

- **Databases:** The system is able to load values from different types of databases. Currently connectors to MySQL, SQLite and DB2 (Oracle) databases are implemented, but it is also possible to attach other database systems easily.

- **Random values:** Randomized values can be created by the system itself. They can be used to test hypotheses for coincidence. It is possible to define upper and lower bounds for the random values. It is also possible to lock the values for one run of the rule interpreter so that a value, that is used by different rules, stays the same for a complete run. That is necessary if the rules depend on each other and use the same random value so that a inconsistent state would appear if the value changes between the inference of the different rules.

- **Time values:** These values are timestamps that are used to check if a date lies in a specific period. Examples for time values are the current time or given points of time. With time values it is possible to do a trend analysis on a input value by comparing the value at different points of time.

The rule solver can be triggered in two different ways. When the system is in the time based mode, the rule manager checks the rules on a fixed timebase that is predefined in the configuration of the system. If the values change continuously the time based mode is a good choice. It assures that the state is checked in fixed intervals. The other possibility is an event based approach. The rules are interpreted every time the systems gets new data. The load of the system is minimized in times where no new data is acquired because the interpretation of rules in these times would bring no new results.

In order to process the rules, the solver builds up a tree-graph of the rules and their dependencies. Every time the rules are processed, the solver fills in the sensor values, searches the tree and performs the action of every fulfilled rule. When a rule or a part of a rule cannot be fulfilled, the execution of this branch stops. This helps to keep the efficiency as high as possible because the solver ignores the parts of the tree that cannot fire an action.

5.2.2.4 Actions and Action manager

After a rule has fired, the action manager executes the corresponding action. Depending on the platform, the amount of possible performed actions can differ. When it is running on a smartphone it can communicate via data transmissions, SMS or phone calls. On a server it benefits from the fast connection and high computing power. Currently, the framework is able to perform the following types of actions:

- **Visualization:** A lot of results can be visualized in various forms. The variety of display options allows the user to chose the most informative form. Until now there are four different types of plots implemented: line plots, scatter plots, histograms and correlation plots. The visualization functionality can be easily expanded like the other features of the framework. Different visualizations can be seen in section 5.4.

- **Logging:** The simplest action is the logging functionality. The action prints messages or values on the default debug console of the particular platform. It can write these messages in text files, too. This function is used to store information that is useful for the developer or to test some functionality.

- **Variable evaluation:** The action handler for evaluating variables is a hybrid function. It can be an input source for rules and an action at the same time. It is used to manipulate variables or to realize counters. After manipulating a value, rules that depend on that variable are re-checked. The possibility to manipulate variables empowers the system to emulate a Turing machine. With the states stored in variables and the transitions modeled in concatenated rules it is possible to build a Turing machine which makes the framework Turing complete [133].

- **Database updates:** Manipulated values or new gained knowledge has to be stored. Therefore it is possible to store these values in a database. This could be the same database where the framework loads the input values from, but it is also possible to write into another database.
- **Executing system commands:** Actions can also be system commands that are executed by the framework. Such can be sending an email, transferring pictures from a camera or other things the device is capable of.

5.3 Integration into the telemedicine system

The TARDIS framework was integrated into the telemedical system as a distinct module. Figure 5.6 shows the interfaces between the two frameworks. The rule editor of TARDIS is rendered as a module in the user interface of the telemedical system. There the user can define rule sets, that are stored as XML files, that can be interpreted by the rule solver. The solver uses the database interface to collect the needed data. Afterwards the results can be displayed and stored in the telemedical framework. For complexer analysis methods, the rule solver uses a collection of data mining algorithms that are implemented in Python (see section 5.5.2). The vast amount of data received from the sensors can be used for detailed analysis with the following three goals:

- reduce the workload of the physician,
- gain new knowledge of the monitored diseases, and
- support the patient who is using the telemedical system.

5.3.1 Workload reduction

In the Tele-Service-Center the framework was used to provide a back-end data analysis and filtering to reduce the workload of the medical staff. First, analysis functions were implemented and tested in the central analysis server to gather additional information like the number of oxygen desaturations at night. Alarms could be generated for specified conditions. Via the telemedical work place a nurse supervised the patients and provided medical support when needed. Filtering functionality allows the physician to let the patient list be ordered by their health status. The definition of the health status can be set by the physician to provide maximum flexibility. The graphical rule editor is integrated in the telemedical work place and allows the physician to create rules for filtering or analyzing the data. It is also capable of creating rules for each patient individually. Rules that are meant to run on the patients device are uploaded to the device automatically. This functionality was designed to automatically give feedback about the treatment to the patient. By using the rule

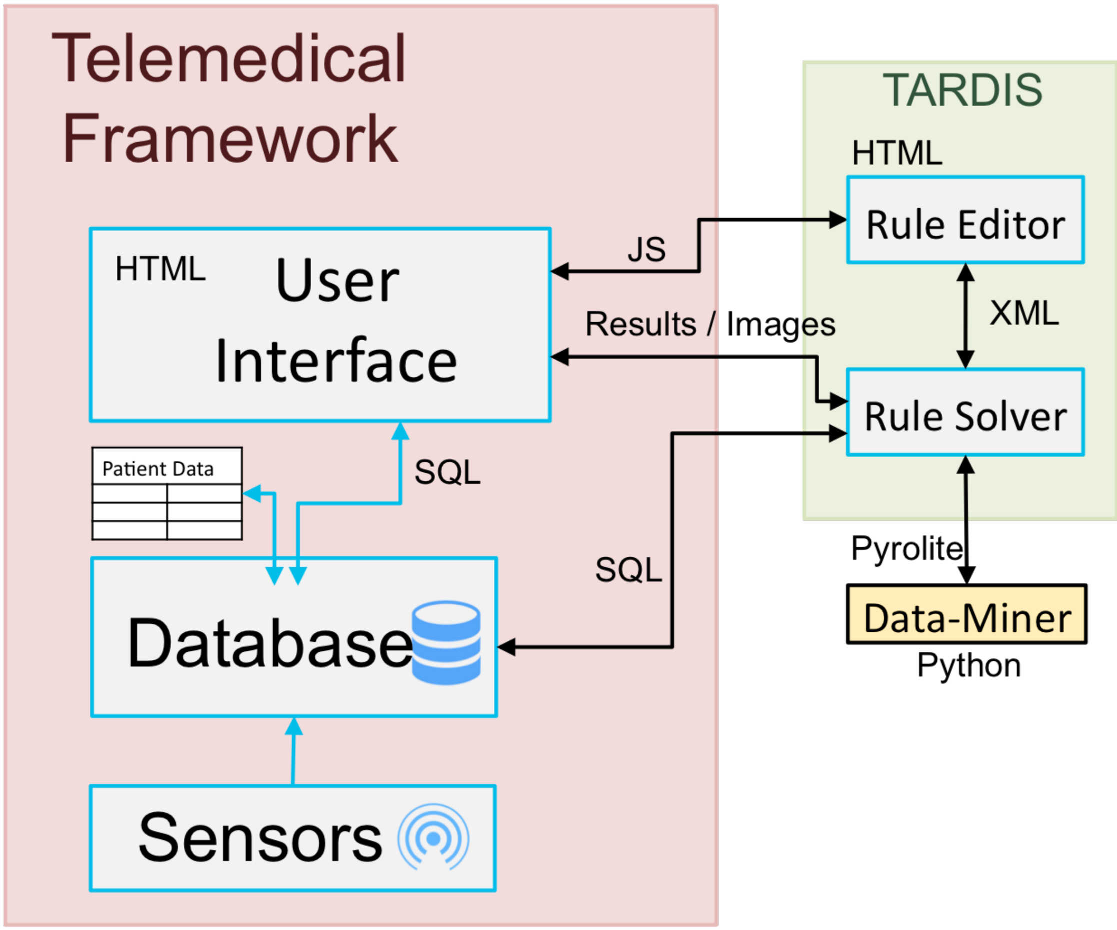


Figure 5.6: Integration of TARDIS into the telemedical framework

based framework the feedback can be individually adapted to the patient by the physician.

5.3.2 Knowledge acquisition

The system collects lots of data from various patients and various sensors and stores them in a database. This leads to a big pool of data that can be used for further analysis. Some diseases are well investigated, others have unknown progressions. Analyzing the data of many patients suffering from the same disease, can provide new insights. The physicians are interested in detecting trends in the data of the patients or correlations between parameters. Therefore an interface for cross-patient analysis has been implemented. This allows the implementation of algorithms and statistical evaluations which access a large amount of samples. The results give new knowledge of the diseases progression or unknown correlations between parameters. Due to privacy issues and restrictions by law, the data is used only in anonymized form and with permission of the patient. The production system will use only data from patients who gave permission for cross-patient analysis.

5.3.3 Supporting the patient

The rule interpretation framework mentioned above can be used to create rules for preprocessing of the sensor values directly on the patients device. Consequently, the physician creates the rules and has the possibility to transmit them to the patients device via the communication link used for data transmission. The patients device is then able to preprocess the data and react to critical situations even if the communication link is not available. The computation on the mobile client can also be used to provide feedback to the patient how effective the treatment is.

On the patient side the framework can provide autonomy functions and a fast and effective preprocessing of the acquired data. The collected data is normally transmitted to the server of the telemedical Tele-Service- Center automatically whenever new data and a communication link is available. This is one simple scenario where the decision framework can be used to provide local autonomy using the internal sensors of the smartphone as additional data sources. The smartphone's internal sensors can also be used to replace other sensors. The activity of the patient can be measured with the gyroscopes inside every modern smartphone. Using the GPS data allows a data transmission depending on the current location of the patient. It can also be used to fuse it with other sensor data to validate some results. The on-site data analysis enables to react to uncertain medical situations in real-time, like triggering an additional data transmission to the Tele-Service-Center for immediate medical supervision.

5.4 Use Cases / Examples

In order to test the rule based system and to identify areas for extension of the framework, we developed several use cases, that represent the expected usage in an everyday medical setting. The examples were designed in close cooperation with physicians. The use cases were developed with rising complexity to push the framework to its limit and identify additional potential for improvement. First, the use cases are generally described to point out the requirements to the framework. Afterwards, in section 5.4.6, the use cases are performed with real data, that was acquired from the telemedicine framework.

5.4.1 Threshold test for single values

When physicians are tele-monitoring patients a lot of data is generated and transmitted. The doctor wants to define thresholds for vital parameters that mark abnormal or critical situations. Such parameters are pulse or saturation of peripheral blood with oxygen (SpO2) values, that are continuously measured. In our scenarios this could be utilized when COPD patients are monitored at home (see section 4.2.2) or when home dialysis patients are doing their treatment at home (see section 4.2.1). In the stream of the data every incoming value is tested for the thresholds. When the rule matches the defined action is performed. In our use case the physician defines a rule that tests the incoming pulse values of patient A. The thresholds are defined at 120 (upper bound) and 60 (lower bound). The rule created in the rule editor can be seen in figure 5.7 (left side). The doctor wants to be informed about values above or below the thresholds. Thus, the action sends a message to the doctor if that is the case. The matching of a threshold test is depicted in figure 5.7 (right side). Rules can configured that they fire once the first time when the defined conditions are met. Otherwise the action can be performed every time a value is over/under the threshold. Comparisons within the rule editor were confined to the usage of single values. For this use case, a function comparing several data with a single value is required. Thus a new *Threshold* module is designed for the rule editor (see fig. 5.8). In the process, one input is occupied by a data source and a second one by a Double value. The expert can expect various results from the *Threshold* function. Depending on the application a graphic display of the threshold test can be a sufficient result. A plot-constraint can be given as an Integer to illustrate a graphic. No graphic is generated if 0 is specified, else-wise it is. But if values from the threshold test should be further applied, they have to be available as input signal for continuing rule editor modules. For example only values above a threshold can be of note. Five versions can be chosen from for the output of the threshold:

- **Binary Top:**
  In the process a single Boolean variable is returned. If the input signal has at least one value exceeding the threshold, `True` is returned, else-wise `False`.

- **Binary Bottom:**

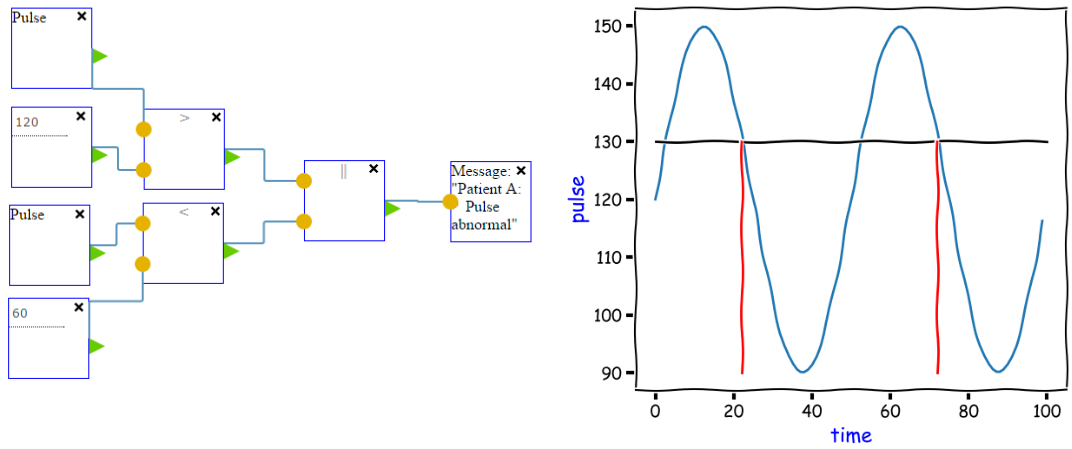


Figure 5.7: Use case 1: Example in rule editor (left) and exemplary visualization of a threshold test (right)

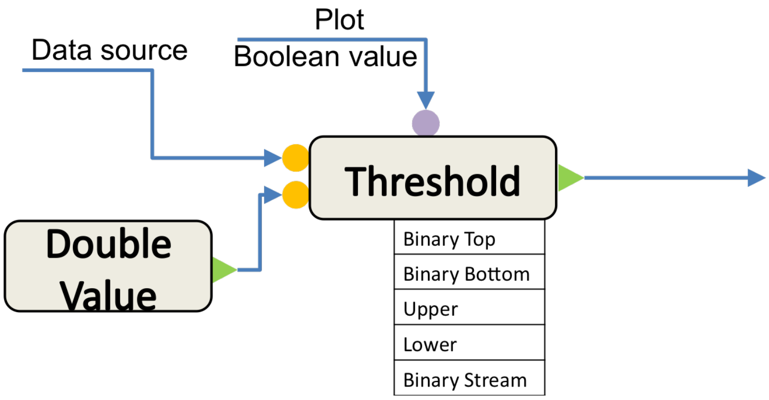


Figure 5.8: Component Threshold

Similar to Binary Top an underrun of the threshold is tested. Returns `True` if at least one value underruns the threshold, else-wise `False`.

- **Upper:**
  Here, all data exceeding the threshold are returned. Exceeding data are left at their current value, whereas remaining data are set to the threshold at the corresponding time point.

- **Lower:**
  Lower is reverse to the Upper function and sets all values above to the threshold. Data beneath the threshold are left with their original values.

- **Binary Stream:**
  Every single input value is compared to the threshold for output of Binary Stream. 1 is noted for the corresponding time point if the value is equal to or above the threshold. If the value lies beneath, 0 is noted. Thus the output is containing binary data at the time points, according to an exceedance or undercut of the threshold, respectively.

5.4.2 Trend analysis

Changes in the body weight of a patient can be a sign for an evolving problem. In the case of home-monitored COPD patients a gain of body weight can indicate a problem with the lung function. Dialysis patients typically gain weight between two dialysis treatments. But when the patient is gaining weight with an increased speed the kidney function might have decreased. Gaining body weight over a short time is mostly due to accumulation of water in the body. To detect these trends, that cannot be seen in the normal spot measurements, the doctor selects a trend analysis to examine the patients body weight. The exemplary rule is depicted in figure 5.9 on the left while the resulting visualization of the trend analysis is shown on the right. The trend analysis module was added to the TARDIS framework to allow these kind

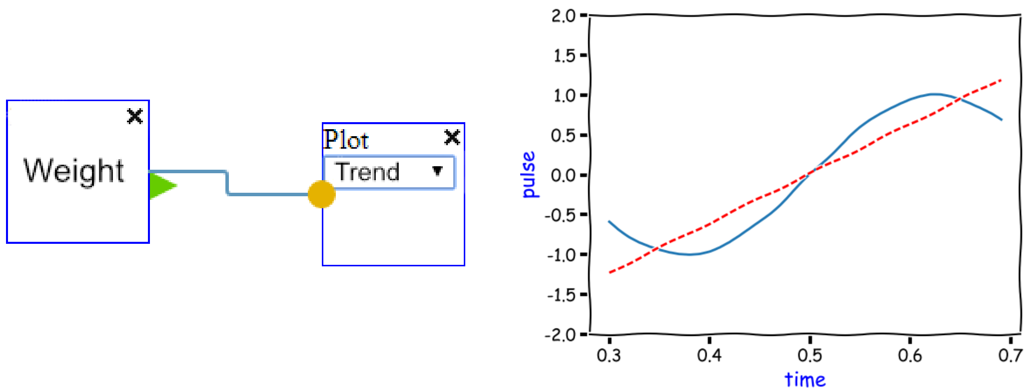


Figure 5.9: Use case 2: Example in rule editor (left) and visualization of trend analysis (right)

of analysis. The visual representation of the module in the graphical editor is shown in figure 5.10. It takes the values from the source and plots a trend graphic. Via a constraint block a maximum value for the slope can be defined. When the slope of the calculated trend exceeds the given value, it is marked in the plot. Additionally, the output of the trend module is triggered, e.g. to raise an alarm.

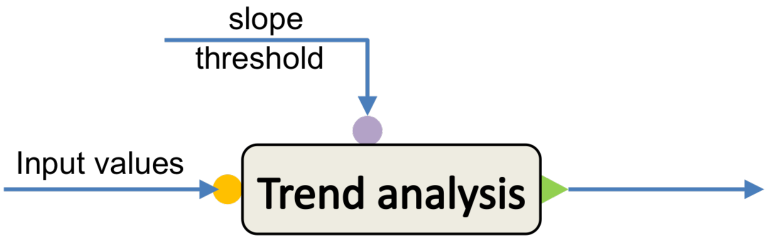


Figure 5.10: Component Trend

5.4.3 Quantile

The use of a threshold function is often not applicable due to dependencies in the parameters. A good example is the correlation between pulse and activity. The pulse values are very dependent of the current activity level. When a patient is resting, high pulse values indicate an illness while high pulse values during phases of higher activity levels are completely normal. The physician wants to see the pulse values in the same time ranges of the same activity to filter out abnormalities, like a high pulse value while there is low or no activity.

A new module is required to enable the desired functionality in TARDIS. Figure 5.12 shows the structural environment of the so-called “Quantile Function” module. Two value sources are used as input for the module. The upper one is the current value that is to be tested, the other one acts as reference value. It is tested initially at the outset of the function if input data types are the same. In which percentage of data the current values should be contained can be set as constraint. The quantile area between both quantiles is calculated from the percentage. Quantile Function always gives graphical feedback about the result during execution. Besides that, a return value can be further used as Binary Stream (see section 5.4.1) in the rule editor. It defines a binary row of values. Thereby `True` corresponds a value outlying the quantile area at the respective time point. All values inside the quantile area are labeled as `False`.

Quantile calculation is applied to determine the deviation. A quantile describes the amount of values in a sample that are above (or below) a given threshold. An area containing a certain part of training data can be confined by two quantiles. To examine if data behave like a certain part of training data (*perc* in percent), two quantiles ($q_{1/2}$) are determined by the formula below:

$$q_{1/2} = 0,5 \pm (0,5 \cdot perc)$$

The quantiles are calculated as an amount of values ($perc$) above ($q1$) and below ($q2$) the median of the sample (see figure 5.11). If $perc = 100\%$ is valid, 100%

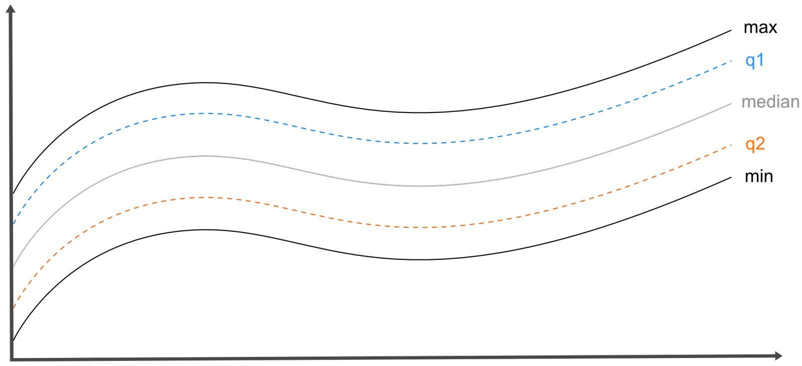


Figure 5.11: Quantile Function

of training data are confined by the quantile function (50% above the median to the maximum and 50% below to the minimum). A 50% quantile is calculated for $perc = 50\%$ according to the median of training data. The Quantile Function builds a "tube" around the median of the training data. One quantile illustrates the values above the median, the other one the values below. The $perc$ value defines the width of the tube. A value of $perc = 20\%$ uses the 40% and the 60% quantile to display an area of 20% around the median of the training data.

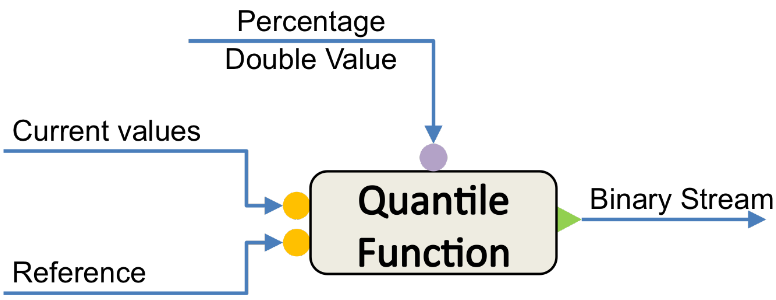


Figure 5.12: Component Quantile Function

5.4.4 Combination of threshold tests

When the medical personnel has defined several threshold values for different vital parameters, they want to have an overview how often the thresholds were reached. The knowledge, that one parameter is more often out of range than another can give a better insight of the patients health status and a better opportunity to find the right diagnosis or optimize the treatment. A visualization is needed where several threshold functions can be combined into one view, that displays the amount of threshold violations in a given period of time. Figure 5.13 shows how such a visualization could be realized. The results of the several threshold functions (depicted on the left side) are cumulated and displayed next to each other in a single plot (right side). A color coding helps to see extreme values very fast. The Plot function is

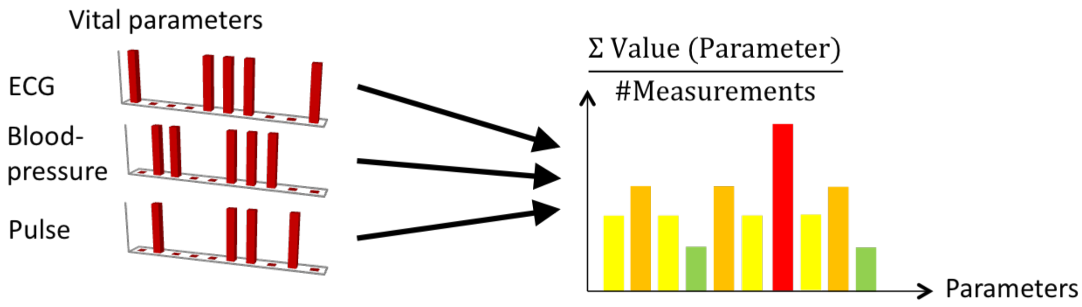


Figure 5.13: Combination of threshold results

expanded by a selection of "Histogram" (see fig. 5.14). This representation helps to identify parameters that are often out of the normal range. Therefore, an optional number of threshold functions on different parameters can be added to the plot function. The histogram plot then shows the amount of values where the threshold was reached.

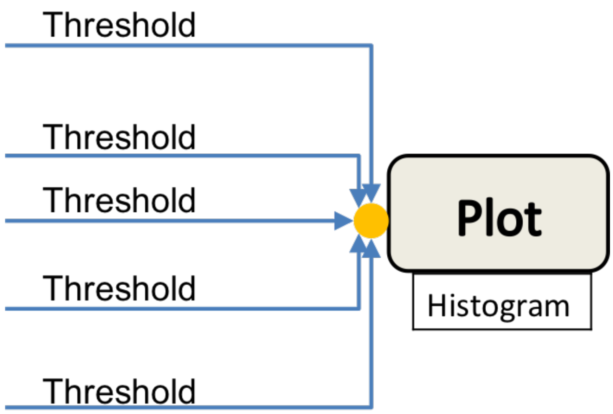


Figure 5.14: Plot module with histogram option

5.4.5 Comparison of health status heuristics

Often it is not clear to the medical personnel which of the defined rule sets are the most expressive to describe the health status of the patient. The goal is to form a rule set that acts as a heuristic to evaluate the patients current status. In order to find the best heuristic we wanted to be able to visualize the correctness of different heuristics, so that the expert can choose the most expressive one for each patient. Figure 5.15 summarizes the workflow to create such a visualization. For each heuristic several reference data, with known results, and test values are inputted. The results, each heuristic calculated for the test values, are fed into an histogram, where the user can see how the different heuristics performed on the data to assess which heuristic fits best for the current data.

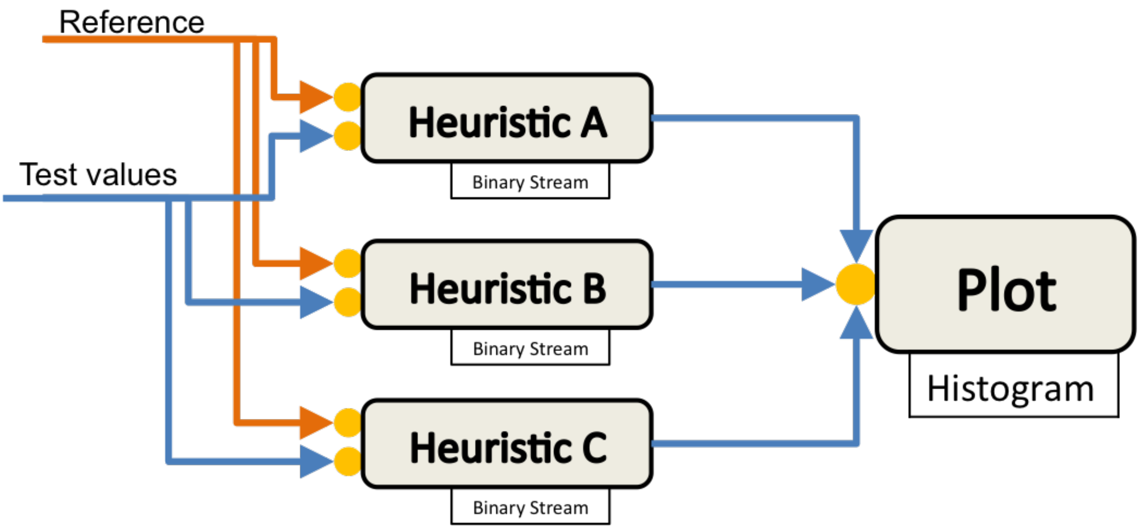


Figure 5.15: Testing different heuristics to find the best one

5.4.6 Results

We used the data, we recorded from the patients during our test of the telemedical framework, to evaluate the previous defined use cases for the TARDIS framework (cf. section 5.4). The results are presented in the following section.

5.4.6.1 Threshold test for single values

The doctor wants to monitor the SpO2 values of one patient. He defines a rule, that performs a threshold test on incoming SpO2 values, to highlight values that are beneath 90% oxygen saturation (figure 5.16). The resulting plot (figure 5.17) shows the measurements of the oxygen saturation over several weeks. The threshold violations are highlighted in red. Since there are only 5 single events, the physician rates the patients status positive. A more detailed view of the results can be seen in figure 5.18.

5.4.6.2 Trend of body weight

The physician needs to monitor the body weight of a COPD patient. Increasing body weight can be caused by accumulation of water in the body which indicates a worsening of the functionality of the lung. A test for the trend of the body weight could therefore be used for an early detection of an exacerbation and allow a proactive treatment to prevent an exacerbation. A first view of the data (figure 5.19) shows, that there are some outliers in the data. As it turned out later on, the granddaughter of the patient has used the patients' scale some times and caused

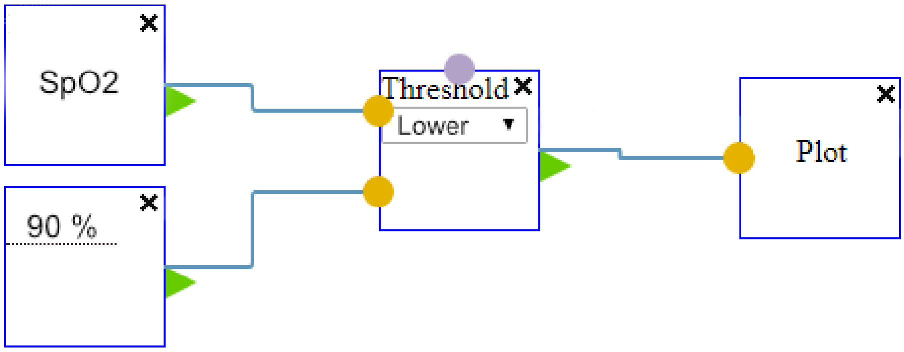


Figure 5.16: Rule for plotting the threshold test of SpO2 values

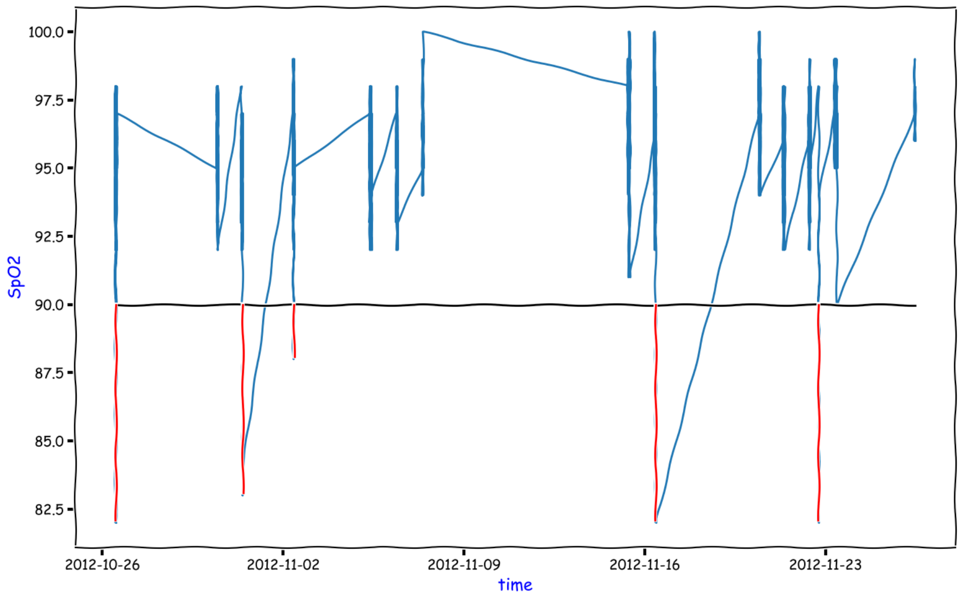


Figure 5.17: Resulting plot of the threshold test

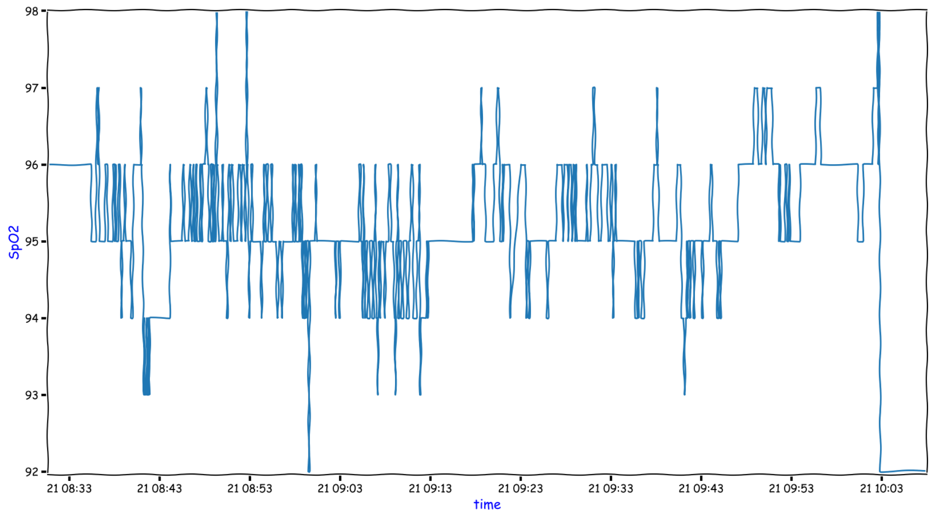


Figure 5.18: Detailed view of the results from the threshold test

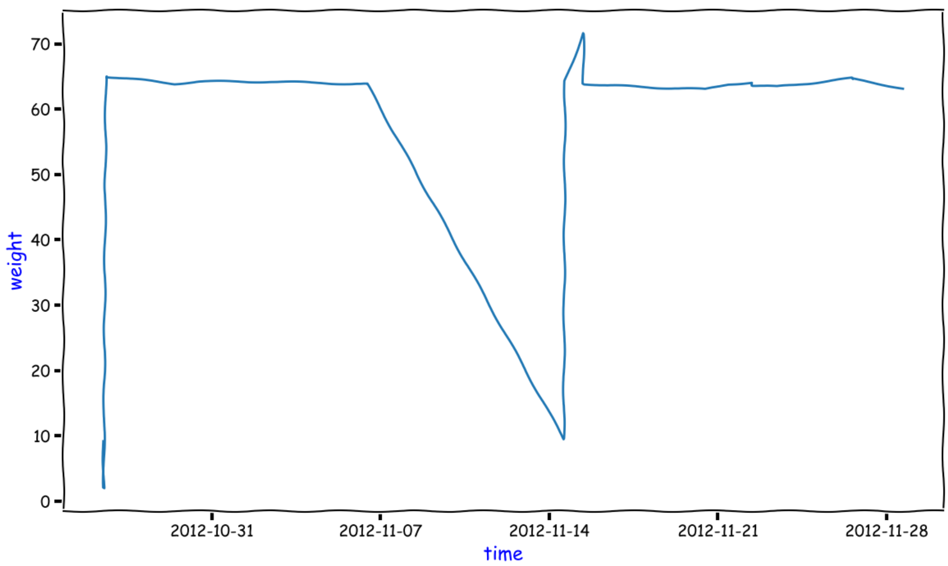


Figure 5.19: Data of the patients weight, sorted by the time of measurement

the extreme low measurement values. To filter out these events, the doctor adds a threshold test, that outputs all values above 20kg. The cleaned output is depicted in figure 5.20. Afterwards the trend function is added to the rule. Figure 5.21 shows

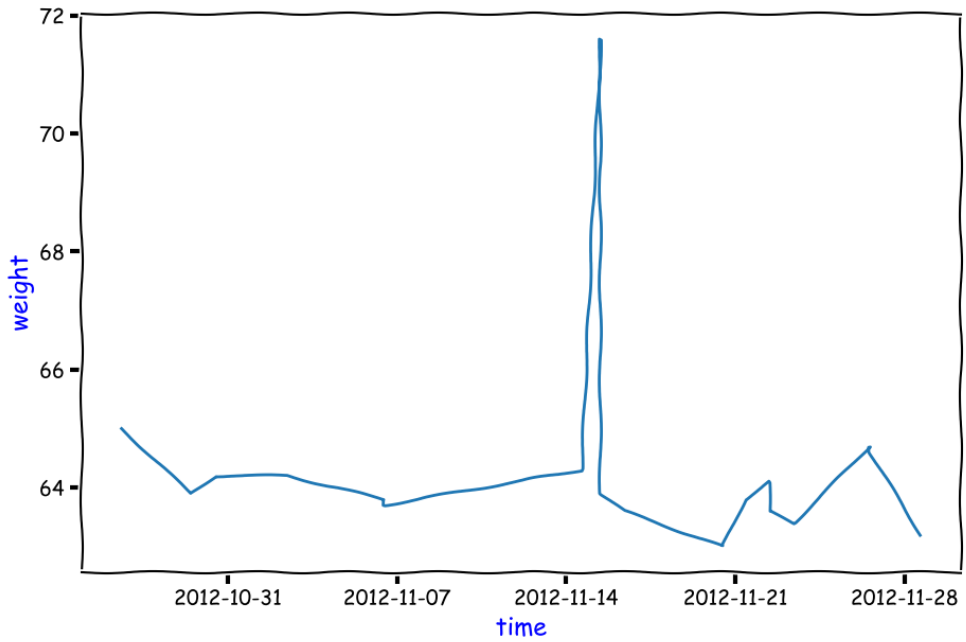


Figure 5.20: Cleaned data without anomalies

the completed rule for this use case. The result (figure 5.22) clearly shows, that the body weight has a slightly decreasing trend, that is no reason to worry about. The reason for the rather high peak has to be clarified, but it is very likely another artifact.

5.4.6.3 Quantile for pulse values

Sometimes it is necessary for the physician to get multiple data sets from the patient that are comparable with each other. To be able to interpret the current status of a COPD patient better, the physician asks the patient to walk some stairs at his home while monitoring pulse and activity. This measurement should be performed once or several times, while the patient is in a good condition, to generate reference data, that can be compared with future measurements. When the patients health status is unclear, the doctor asks the patient to perform another measurement while walking the same stairs. He then uses a rule-set, he defined earlier (cf. figure 5.23), to interpret the incoming data. The rule-set uses the quantile function to compare the different measurements. One or more measurements that were taken when the patient was in a good condition are considered as reference. The measured activity data helps to timely synchronize the data streams, so that the pulse values can be

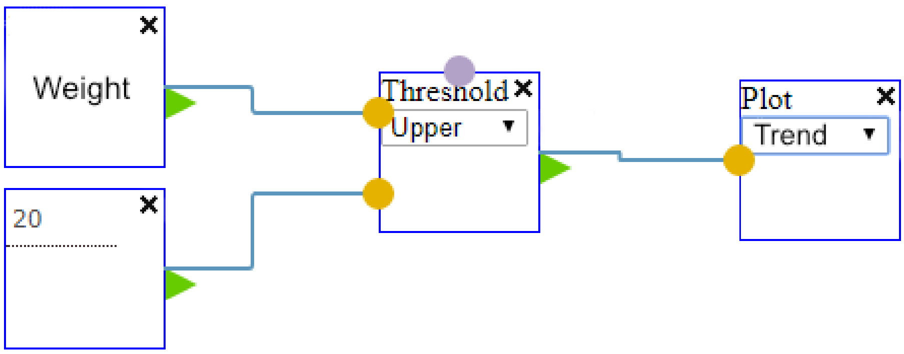


Figure 5.21: Completed rule for a trend analysis of the patients body weight

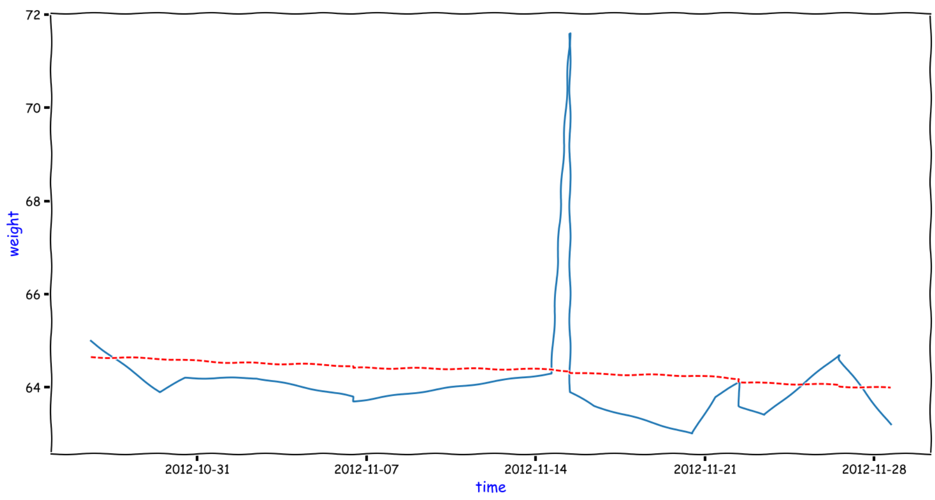


Figure 5.22: Resulting plot of the trend analysis

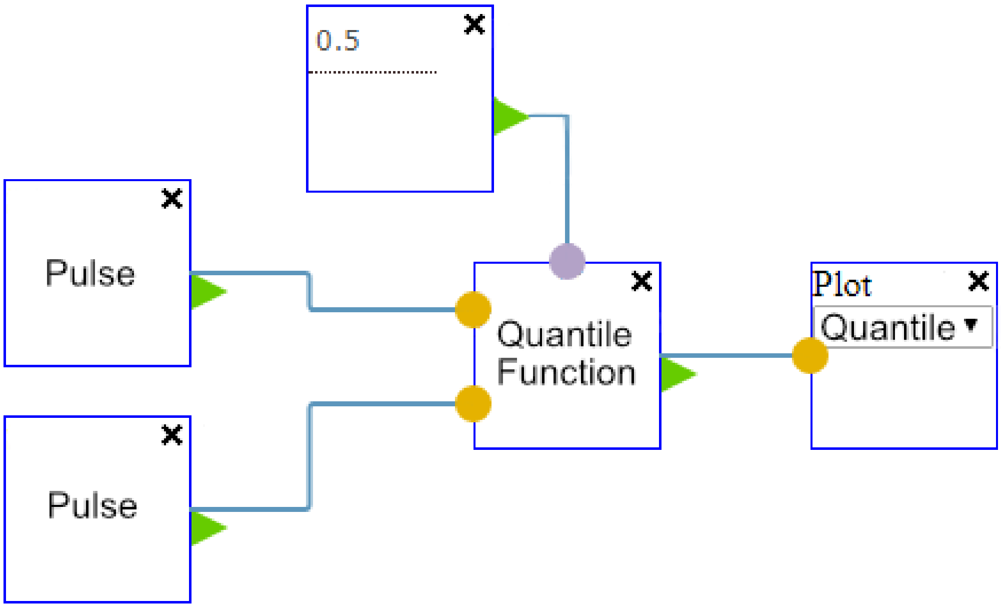


Figure 5.23: Rule for comparing a set of pulse values with other value sets using the quantile function

compared. The quantile function can be parametrized with a value that defines the size of the quantile area. The default value of 0.5 generates the output that can be seen in figure 5.24. The high pulse values, that result from walking the stairs, are clearly visible. The new values are very often marked out of range. The doctor

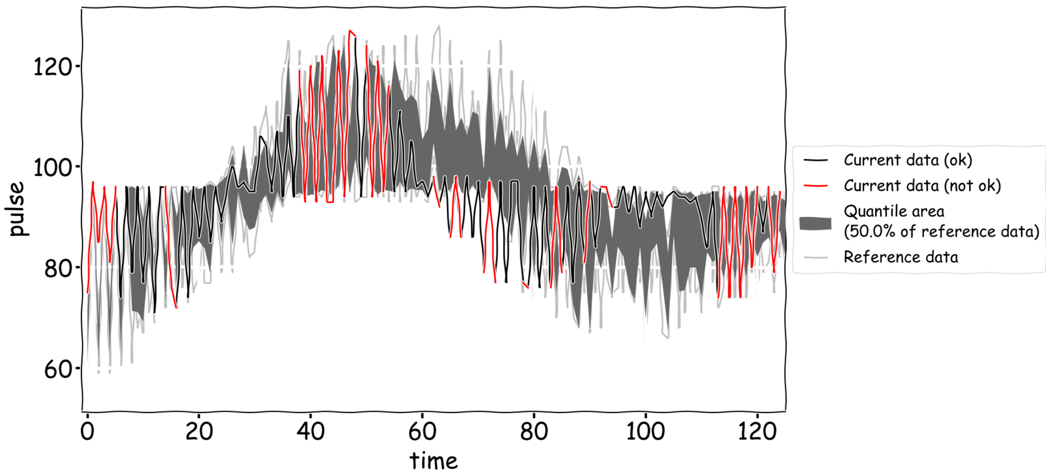


Figure 5.24: Quantile function of the pulse with a 50% quantile area

decides to change the quantile area to 75%. The result is shown in figure 5.25. It shows that the pulse value of this measurement are still a bit off the normal values.

The physician notes that the pulse values are increased but not alarming. He makes an appointment with the patient as a precaution to perform detailed tests of the lung function.

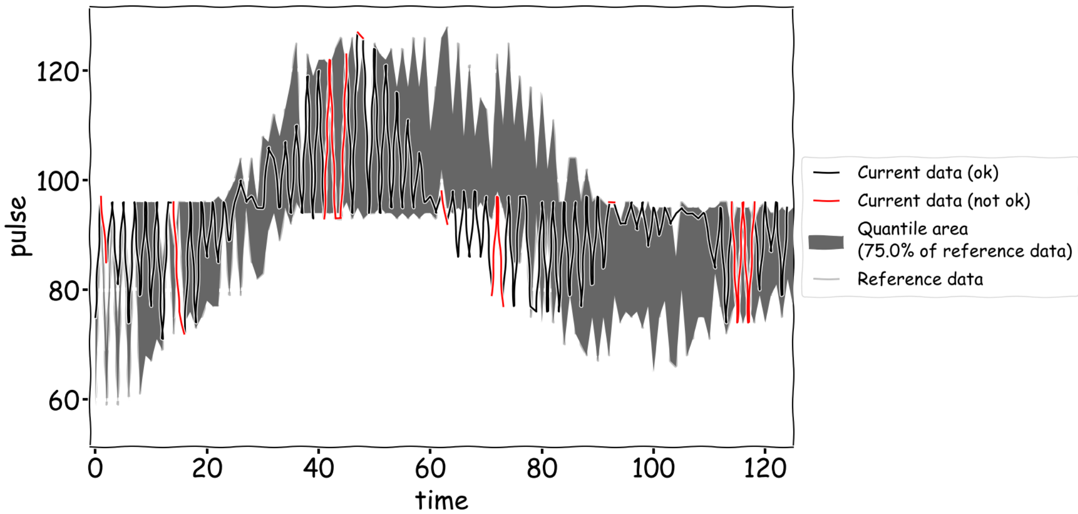


Figure 5.25: Quantile function of the pulse with a 75% quantile area

5.4.6.4 Combination of threshold tests

The doctor wants to compare several threshold tests of different vital parameters. Therefore, he defines a rule-set, that combines the threshold tests of the parameters weight, blood pressure, oxygen saturation and the Forced Expiratory Pressure in 1 Second (FEV1) value, that describes the amount of air one can exhale in one second (figure 5.26). The result should be plotted as a histogram, that shows the amount of threshold violations for the different parameters. The result (figure 5.27) shows the amount of threshold violations for each of the four parameters. The color spectrum helps to easily identify values that are often violating the given thresholds. Here the doctor can see that the patients weight and blood pressure values are not critical. The high amount of threshold exceedance in the Forced Expiratory Pressure in 1 Second (FEV1) values can originate from a wrong threshold value for this patient or a decreasing capacity of the lung due to the COPD disease. In combination with the large amount of low oxygen saturation events, the doctor decides that a further diagnosis of the lung is needed, to determine the current state of the disease and plan the next steps. These could include changes of the medication or treatment and adjusting the threshold values to the new situation.

5.4.6.5 Combination of health status heuristics

To gain a overview of the patients health status the physician uses the different threshold tests, defined in the last section 5.4.6.4, to display on which days the

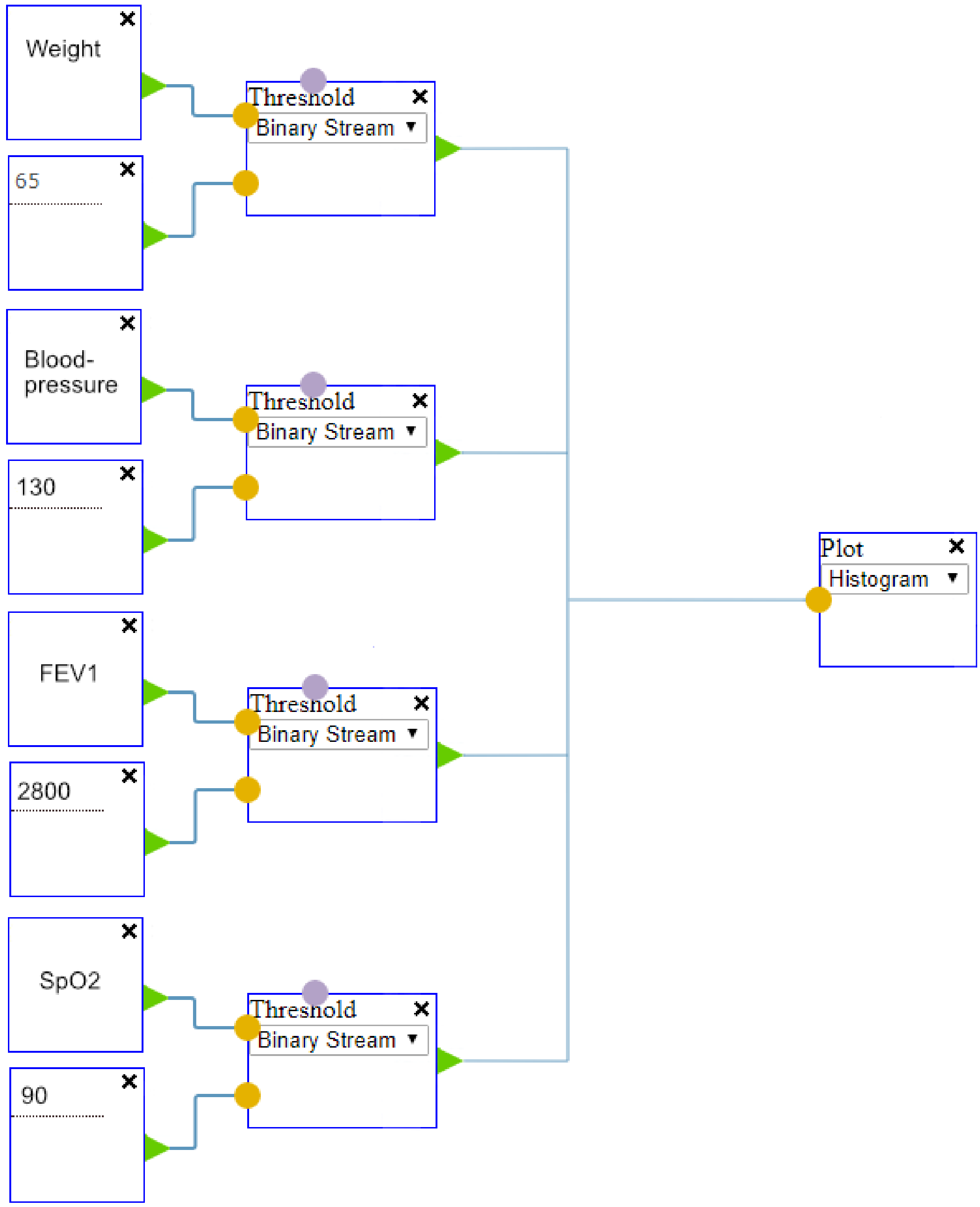


Figure 5.26: Rule-set for creating a histogram graph of different threshold tests

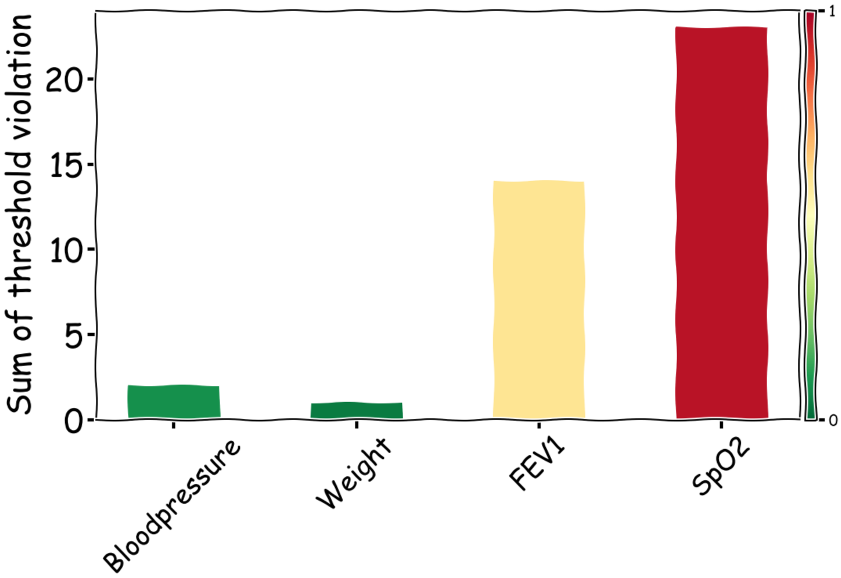


Figure 5.27: Histogram plot of the amount of threshold violations

health status of the patient was worse in reference to other days. This test can be used to evaluate different heuristics, too. Combined with a feedback from the expert one can see which heuristics describes the health status of this patient the best. That way the best heuristic for each patient can be found. In our example the doctor used the threshold tests, like in the rule-set depicted in figure 5.28, to get the result depicted in figure 5.29. The first days of the displayed period were clearly worse than the rest. The patient used his drugs, meant for such situations. Afterwards his status stabilizes.

5.5 Usage in other fields of applications

Since the telemedicine framework and the rule based decision framework are designed to be as generic as possible we wanted to test the integration of the systems in a completely different field of application. The frame of this test was the three-year research project "MainTelRob (Maintenance and Telematics for Robots)" [134] and its successor "Bayern.digital" funded by the Bavarian Ministry of Economic Affairs, Infrastructure, Transport and Technology. The project consortium of MainTelRob consists of the Zentrum für Telematik e.V., KUKA Industries and Procter&Gamble. The projects aim to develop a telemaintenance infrastructure for an industrial robot in a plant producing plastic parts for electrical toothbrushes.

Two systems, that were developed in the project MainTelRob, are interacting with the telemedical framework and the TARDIS modules to analyze the robot data and perform data mining:

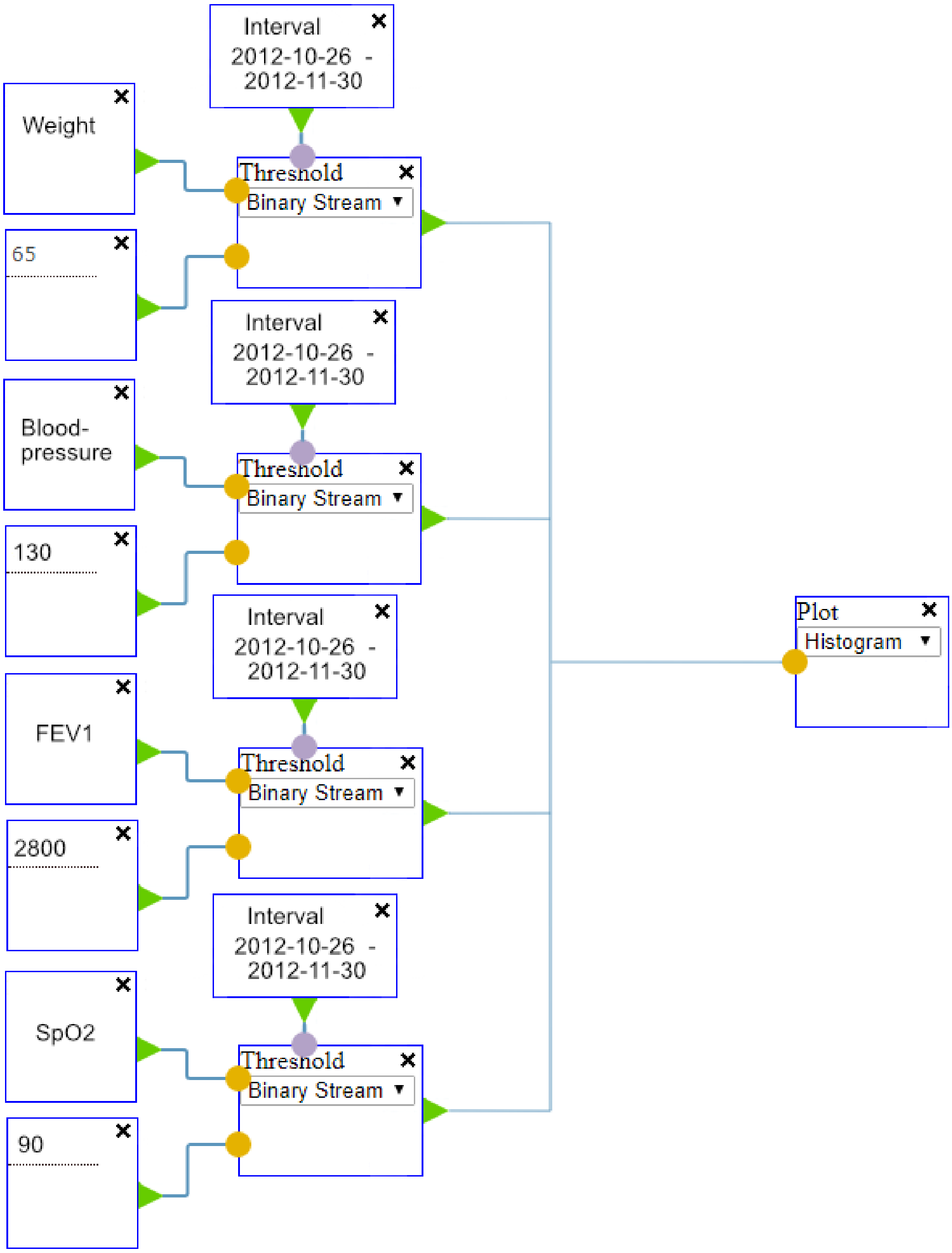


Figure 5.28: Rule-set for creating a time-based overview of the patients health status using different heuristics

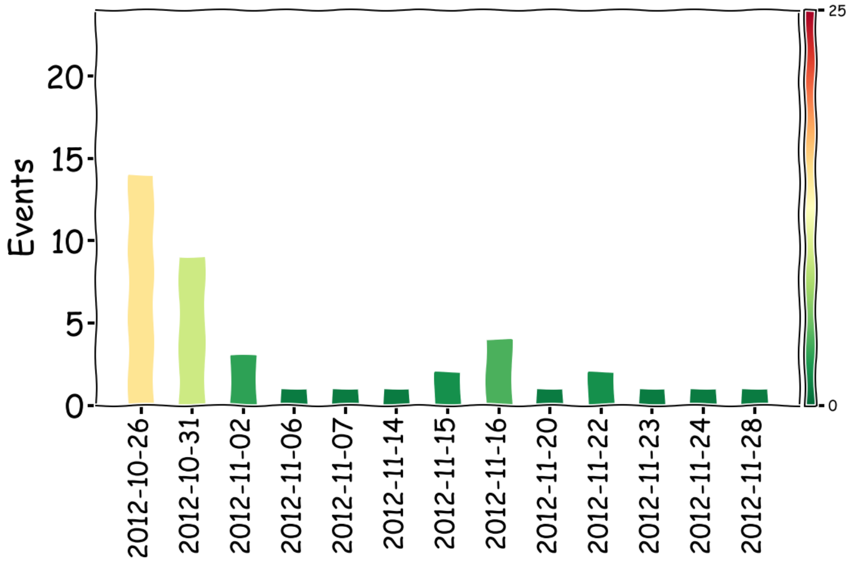


Figure 5.29: Histogram plot that shows the amount of events per day

Adaptive Management and Security System (AMS) The AMS framework is the system, that represents the telemaintenance infrastructure. It contains all the necessary modules for the interfaces, communication links and all the other parts of the telemaintenance system.

Complex Analysis Tool (CAT) CAT is the module, that is responsible for the data analysis and the direct communication with the TARDIS framework. It uses the rule solver to perform the analysis of the data and displays the results in the defined spots of the AMS framework.

For the combination of the different systems and working with the robot data the following steps were taken: First the data from different sources are collected and added to a data storage (chapter 5.5.3). The data is then preprocessed for the following steps (chapter 5.5.4). For the realization of rule based data mining approaches the TARDIS framework was integrated into the software that is used in the project MainTelRob. The functionality was tested in several defined scenarios (chapter 5.5.5). The results of the testing scenarios 5.5.6 are reused for pattern recognition in a graphical user interface (GUI) for knowledge extraction.

5.5.1 Interfacing with TARDIS

When combining TARDIS with CAT, a high value is set on the communication of clearly defined interfaces and a preferably modularized work. The designed groups of scenarios are integrated in the rule editor, and further rules can be applied. The rule editor is integrated as an HTML file into the AMS framework and communicates with the CAT service via javascript. The rule solvers's data exchange with the

CAT service is executed by Inter Process Communication (IPC) between the two javascript processes. Communication between CAT and the rule solver is depicted

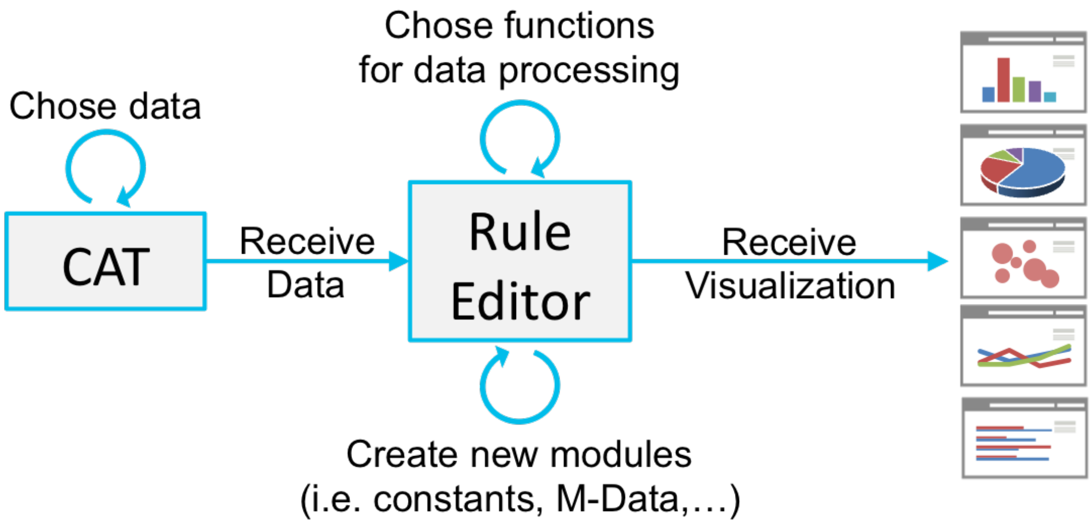


Figure 5.30: Interactionmodel

in figure 5.30. First, a rule designed in the rule editor is started. Then the rule solver prompts correspondent data from the database of CAT. Data are defined by variable name, cycle constraints, and time constraints. Finally, the rule can be executed with the data and a result is returned as a message to CAT, and accordingly a plot can be generated by the *Data-Miner*.
To translate the application scenarios from chapter 5.5.5 to TARDIS, concrete modules are designed, which enhance the functionality of TARDIS. These modules partially require structural alterations of the rule editor:
Modules regularly have a fixed number of input and output signals. However, newly added modules need a flexible number of input signals. Besides the regular input and output signals, so-called *Constraints* determine auxiliary conditions for some of the rule editor's functions. *Constraints* are managed as a new signal of a module and marked with a violet circle on the upper side of a module. In case of a *Constraints* not being chosen, the function automatically uses a default value. Further, some modules require a flexible type of output signal, because the subsequent use strongly depends on the module's output. This is put into effect by a drop-down menu within the respective modules (cf. chapter 5.5.5).

5.5.2 Data-Miner

Data-Miner designates a Python server, that is connected with TARDIS via the Pyrolite interface. Figure 5.31 depicts the interaction between the CAT software and the TARDIS framework. The library *matplotlib* is used for the visualization of translated data (cf. [135]). Data structures are managed with the help of the *pandas* library (cf. [136]). So-called *DataFrames* arrange data in an order of lines (Index)

and columns (Columns), similar to tables. Single columns from *DataFrames* can be handled as *Series* , which respectively assign a value to an index.
Robot data (M-Data, cf. section 5.5.3.1) are codified from the database via cycle number to a tree map of time points with values [(HashMap<Long, TreeMap<Long, ? extends Object{>}{>}). Python uses the data as dictionary, in which a number of time points with values (long : value) is assigned to a cycle number (long), (dict(long : dict(long : value))) and then either can iterate over the entries or convert the whole dictionary into a *DataFrame*.
Data of the Visual Control Point (V-Data cf. chapter 5.5.3.2) are managed as a classification of layer number (Long) to a binary value (Boolean) from the database (HashMap<String, HashMap<Long, Boolean{>}{>}). In the process, data are assigned per String to the name of the corresponding Visual Control Points (VCP). In Python, data are received as dict(string, dict(long, boolean)).
If data is transferred directly from javascript in a *DataFrame*, for every index (in case of the robot a measuring time point) a line is added to the *DataFrame*. With the intervals between measurements not being equidistant, a new index is added for every previously unknown time point in the *DataFrame*. Values for the other cycles rarely exist for the new index, therefore *pandas* backfills missing values as Not a Number (NaN) in the *DataFrame*. Single *Series* have own indices for the values. Regarding the graphic display of data from the database, this means that every column is managed as *pandas.Series* to avoid falsified display by NaNs. To enable the functionality of shifting and magnifying the graphic, a new window showing the graphs generated by Python is opened.

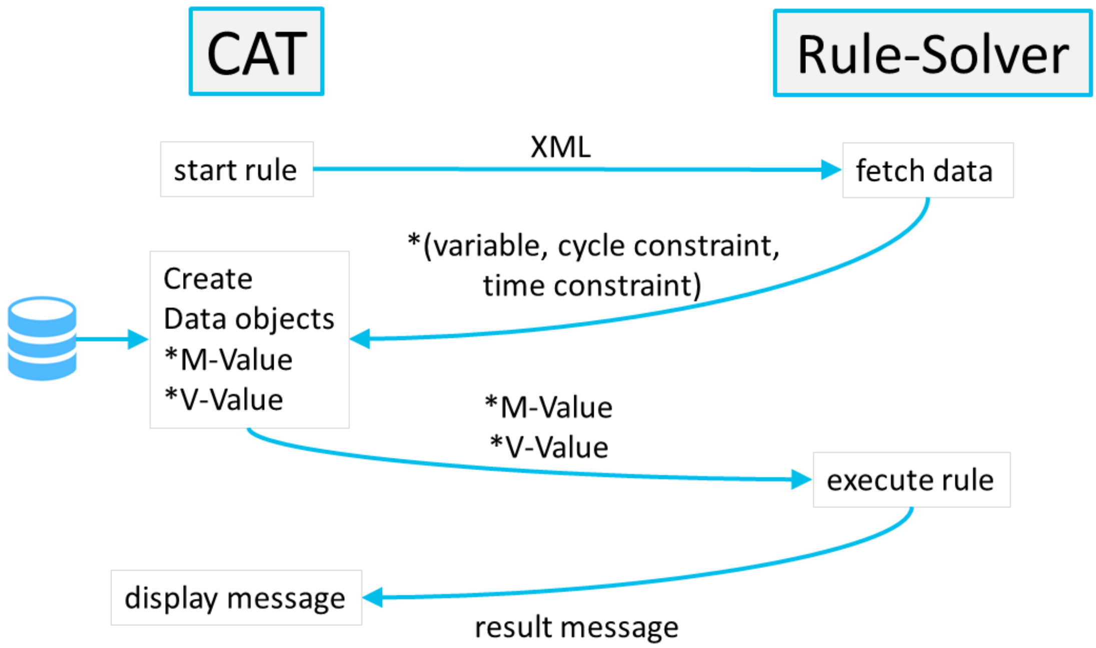


Figure 5.31: Interaction of rule solver and CAT software

5.5.3 Types of data

Handling large amounts of data is a difficult task for every user. Even experts require tools to reduce the amount of data into smaller chunks of data, containing the essential information. The raw data is collected directly from machines and could be collected erroneous. In the MainTelRob project the raw data is collected from two different types of data sources: data is generated from some parts of the industrial robot (chapter 5.5.3.1) while other data is collected by humans at so called Visual Control Points (VCPs) (Chapter 5.5.3.2). Both data sets are stored in a joint database (chapter 5.5.3.3).

5.5.3.1 Machine data

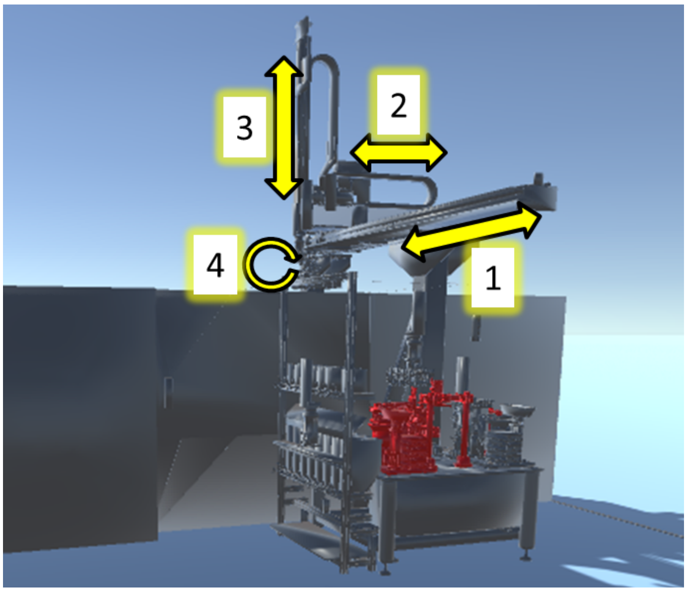


Figure 5.32: The axes of the robot used in the project MainTelRob

Several values of the robots data are stored in a database. The robot can acquire information from other parts of the production unit via the different in- and outputs. The data is divided in three groups: integer variables, position variables and floating point variables. These tables contain the names of the values, that are used in the robot control, and a short description of the values. Most recorded values are discreetly scanned, continuous values. Sometimes binary values, that represent categorical data, are stored in integer variables.
The industrial robot, used in the research project, has four axes that are depicted in figure 5.32. The axes one to three are translational axes while the forth axis with the gripper is a rotational one. The tool itself has further degrees of freedom, but these are controlled over other variables. Some of the data sets are labeled similar for each axis. These values are labeled with indices for the different axes, e.g. _RACTUAL_POS[1] for the current position of axis one.
Each measurement records 54 variables. The measurements are repeated in irregular

intervals between 10.8 and 12 milliseconds. The robots clock is 10 milliseconds (cf. [137]). There are different delays in the recording of the values. One cycle of the robots process takes about 35 seconds. This results in about 3000 measurements per cycle with 54 variables each. In one hour about 133 MB of robot data is recorded. In order to use the machine data for data mining we define which variables are queried from the database:

- one variable x in one cycle i at a time t: $x_i(t)$
- one variable x in one cycle i for the complete period T of one cycle: x_i
- one variable x in n cycles at a time t: $\sum_{i=0}^{n} x_i(t)$
- one variable x in n cycles for the complete period of all cycles: $\sum_{i=0}^{n} x_i$

First the data is combined in the rule editor of TARDIS, then processed in the rule solver. The function M-Data (see figure 5.33) is a draft for the usage of machinery data in the rule editor. The variable can be labeled with a text field in the component. The component also needs two parameters, that constrain the input: cycle and time. Both parameters can be specified as single value, interval or array. If some cycles in an interval should not be considered, the array can be used to specify all cycles that should be processed. If none of the constraints is defined, the complete period of all cycles will be processed. For every given cycle the function returns an array of $[t, x(t)]$ pairs: $[t, x(t)] \cdot n$, with $t \in \mathbb{N}$ is the point in time, $x(t)$ the value from the database for the chosen variable and $n \in \mathbb{N}$ the number of chosen cycles. The value $x(t)$ is represented as boolean, integer or double variable. This structure can represent all of the machinery data mentioned above and is called "M-Value".

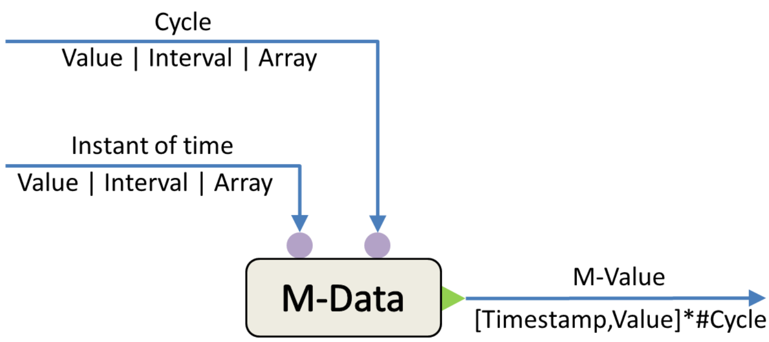


Figure 5.33: Component M-Data

5.5.3.2 Visual control points

In the project MainTelRob we evaluated the use of mobile devices to assist maintenance tasks (see [138]). The attempt is to replace static terminals and to integrate all necessary functionalities into one device (all-in-one strategy). The device can support with manuals or pictures and can also be used to control the robot. In case of remote maintenance the camera of the device can be used for communication with an expert. Figure 5.34 depicts the workflow of a maintenance process with the assistance of a mobile device. Some areas of the machine, that need periodic maintenance, are marked with Quick Response (QR) codes. At these so called VCPs the technician has to perform maintenance tasks. The technician can protocol the current state of this part of the machine and can add a picture of damaged parts or irregularities. Such maintenance tasks could be the check of hoses and wires or cleaning of certain areas. The maintenance tasks are repeated in regular intervals.

Figure 5.34: "Visual Control" function for supporting maintenance tasks (see [138])

The intervals differ dependent on the VCP. The different intervals are 'once per shift', daily, weekly or monthly. Knowing the different intervals is crucial for using data mining techniques. For the analysis of the data only two states are considered: 'ok' and 'not ok'. When performing a maintenance task the technician can choose from two other states too: 'not accomplished' is used when the maintenance task was not performed in this particular shift. We handle these states as 'not ok'. An inspection task is marked as 'not necessary' for example when it is a weekly task and has been performed in an earlier shift. The marking 'not necessary' is treated like 'ok' in this work for simplicity reasons.
Other information to the VCPs is not stored at the moment.

The data used in this work was acquired during a test phase at a real production line.
The data of the VCPs are stored as logical values for the different control points. To be able to use the data with TARDIS a new block is needed for the rule editor: V-Data (see fig. 5.35). Like the time constraints for the M-Data blocks (see chapter 5.5.3.1) a selection of shifts is used as a constraint for the V-Data blocks. Additionally a name can be used to constraint the VCPs. If no name is provided, all stored VCPs are used. The result of the block is an array of shifts for the selected VCPs that contains a single binary value per control point: $[t, x(t)] \cdot n$. While $t \in \mathbb{N}$ is the selected shift and $x(t) \in \{\texttt{True}, \texttt{False}\}$ is the state of the visual control point in the corresponding shift. $n \in \mathbb{N}$ is the amount of selected VCPs. The value `True` is

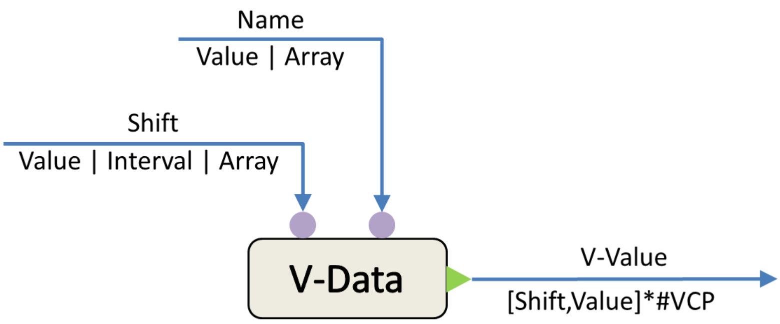


Figure 5.35: Rule block V-Data

used, if the control point is 'not ok'; `False` is used if the VCP is 'ok'. The resulting values are labeled as 'V-Value' in the following.

5.5.3.3 Data storage

All data that has been acquired during the project MainTelRob are stored in the same database structure. The access to the data is controlled by the AMS framework and is realized with a Structured Query Language (SQL) interface in a Java environment. Besides the data of the robot and the VCP data an additional local database is created for internal communication. In the following we make no difference from which database the data is acquired.

5.5.4 Data preprocessing

Preprocessing of VCPs is confined to a hypothesis. If the repetition rate for all values is assumed to be "per shift", only categorical data remain. These can be processed directly via data mining.
Below the data used as testing data in this study are discussed to edit the machine data. Robot data continuously change, but are read in a pulse of <1 milliseconds, like described in chapter 5.5.3.1. For data recording, a macro is deposited on the robot control, which is selected once per program sequence and saves data in the database per robot pulse (10 milliseconds). Measuring time points are set by three variables: date, time in the format hours:minutes:seconds, and millisecond.
Figure 5.36 shows a processed version of variable _RACTUAL_POS[2] of the 54 variables enclosed in the 52 cycles of testing data. The display of raw data and figure 5.36 only differs in the labeling of the time axis. Since the absolute timestamps in the database show very high values and thereby corrupt the axis labeling, the earliest starting point of all cycles is determined and subtracted from all data. Using absolute time stamps from the database, all cycles should thus be displayed successively on the time axis. However, all cycles are indicated in roughly the same time window. Obviously at this point already an error occurs. To compare the course of robot data, the starting points of cycles would have to be changed in the normal case to make all cycles visible in the same time window. The legend of

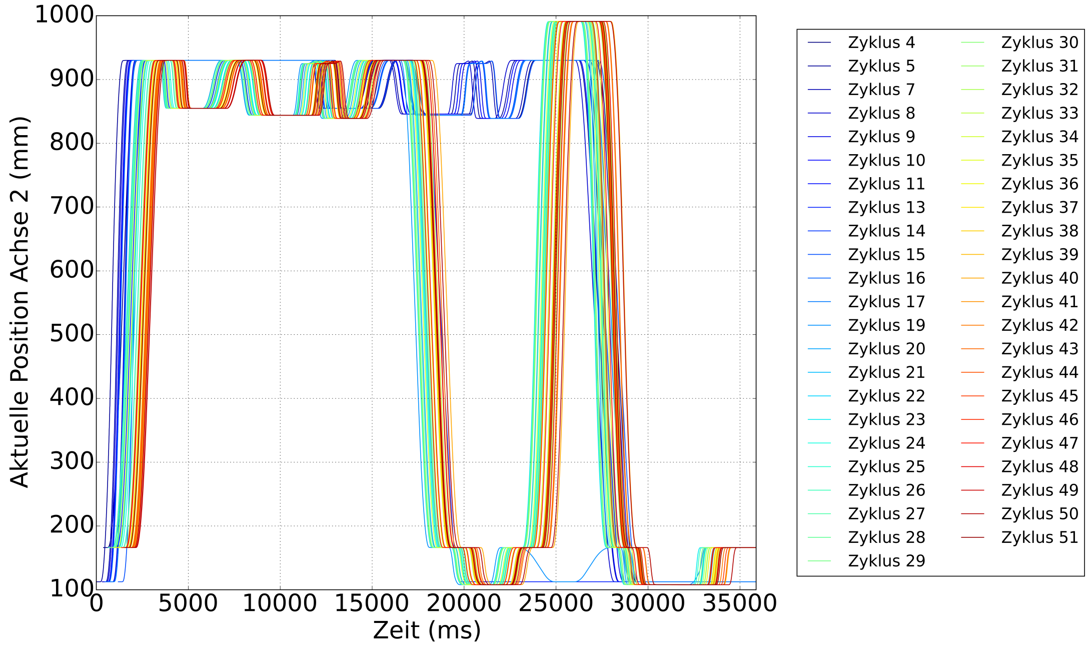


Figure 5.36: Position of axis 2 in all test cycles

figure 5.36 shows that not all cycles from 1 to 52 are listed. That is because some data is lacking in the testing database for some cycles.

The example in figure 5.36 indicates that comparing variables from several cycles is barely possible. The reason for a shifted display of graphs is a mix of several parameters: Cycles have different starting points and various length of complete measuring time. To correct the temporal shift, a slightly modified technique of smallest squares is used: An optional cycle is selected as best-fit curve, to which the remaining cycles are fit best possible. These cycles are shifted on the time axis by a value Δt, until the distance between all points on the position axis and the best-fit curve are minimized. The result is on the one hand, is a shift Δt, on the other hand it is the minimum of the sum of the quadratic fields on the value axis regarding the best-fit curve. The adapted method of smallest squares below is constituted as Least Square Fit (LSF).

In the beginning, an equidistant measuring pulse of 10 milliseconds is assumed for the data. If together with this assumption, LSF is used to correct the shift of the time axis, a falsified result is produced: With the pulse of 10 milliseconds being reneged on in already the first cycle, there are extensions and strains on diverse parts of data. LSF assumes equidistant intervals and thus calculates a fictive time shift. By using this shift to correct the time axis of robot data, a false result is received. As the robot data is not read frequently enough to fulfill the Nyquist criterion, the problem of different intervals cannot be eliminated by Fourier transformation (see [139] for more detailed information). To form equidistant intervals, the data at hand are interpolated on a granulation of 1 msec. Then the LSF is executed for

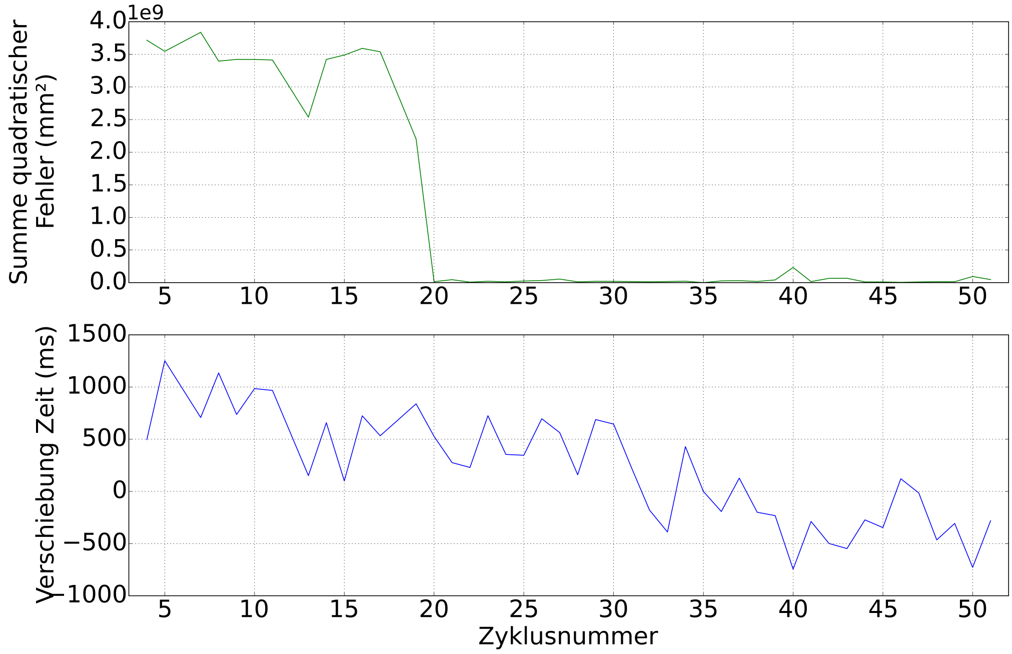


Figure 5.37: Results of the *Least Square Fit* on cycle 35

the interpolated data. In figure 5.37, the result from LSF for the example of the

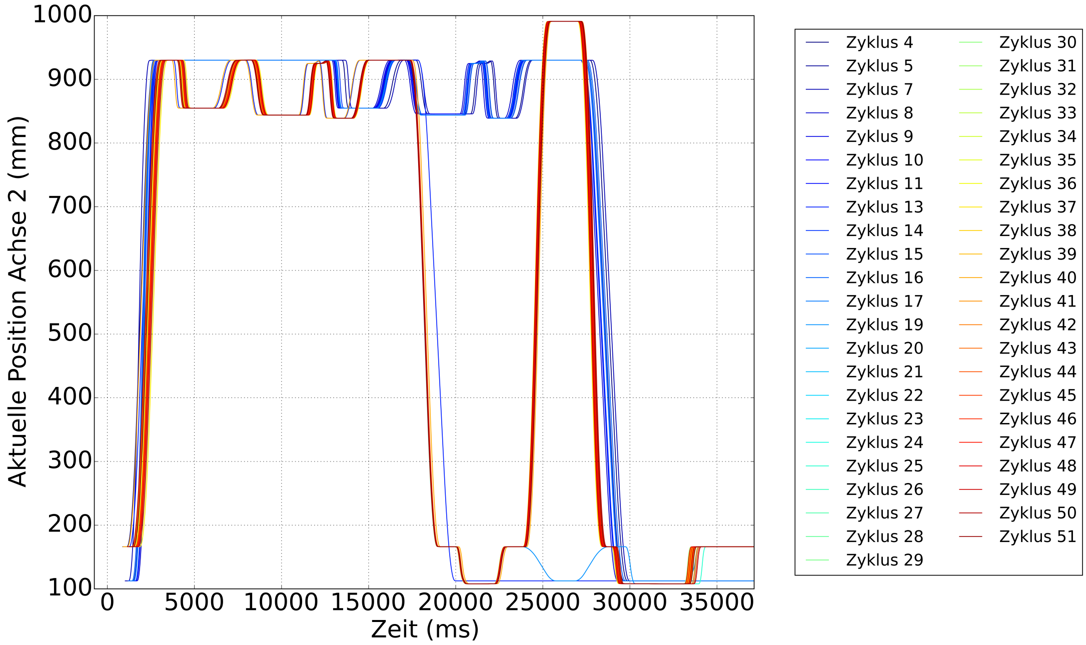


Figure 5.38: Position of axis 2 after applying the LSF on cycle 35

position of axis 2 can be seen. LSF here is determined with cycle 35 as a best-fit curve. Temporal shifts are within a time frame of approximately -0.8 to +1.3 seconds. The value for the quadratic error shows the extent of deviation between single cycles and fixed cycle. Apparently cycles 1 to 19 strongly deviate from cycle 35. This can also be seen in figure 5.38, which shows data after LSF. To sustain

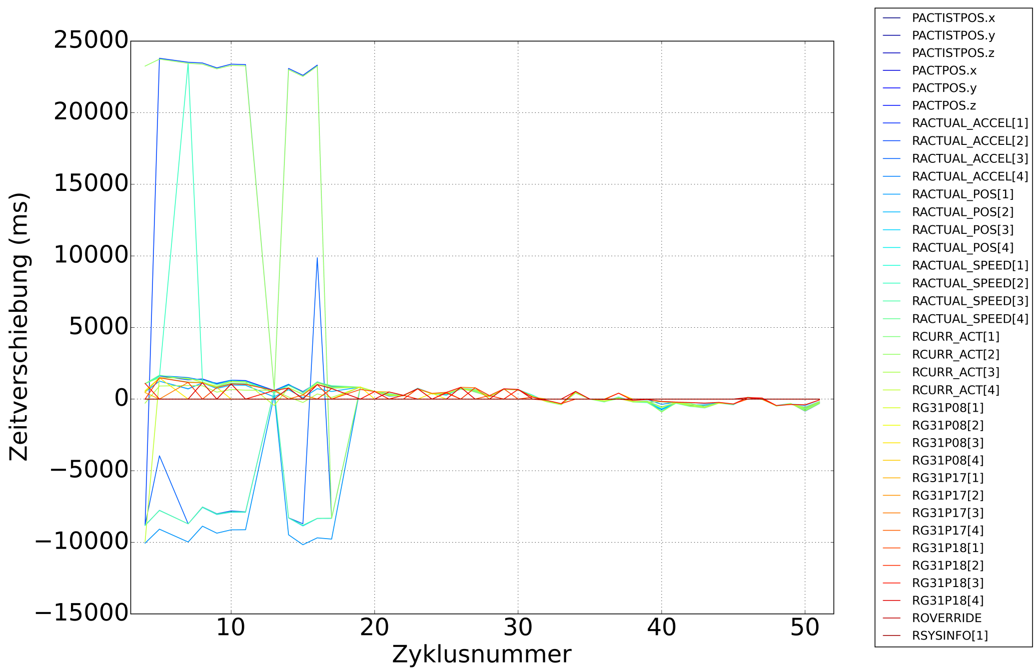


Figure 5.39: Time shift of all floating point values of all cycles with respect to cycle 35

efficiency during run-time, it seems logical to calculate temporal shift of a cycle for only one variable and use the result for all remaining cycles. To test the similarity of shifts, figure 5.39 depicts the determined shift for each cycle and variable. A line symbolizes the temporal shift of a variable in machine data per cycle number. If the assumption mentioned above is true and one calculated variable suffices, all variable-lines would coincide with each other. As figure 5.39 reveals, the shifts in especially the first 19 cycles do not follow a common course. But also the remaining cycles do not show the same curve (see fig. 5.40). For the shift in cycle 35 all tested variables are exactly on the zero point. In summary, comparing machine data over several cycles of LSF has to be done separately for each variable.

5.5.5 Use cases

General use cases are developed, which an expert can comply with the example of an industry robot with the CAT software. Each scenarios's application is described, and emerging requirements for TARDIS are explained.

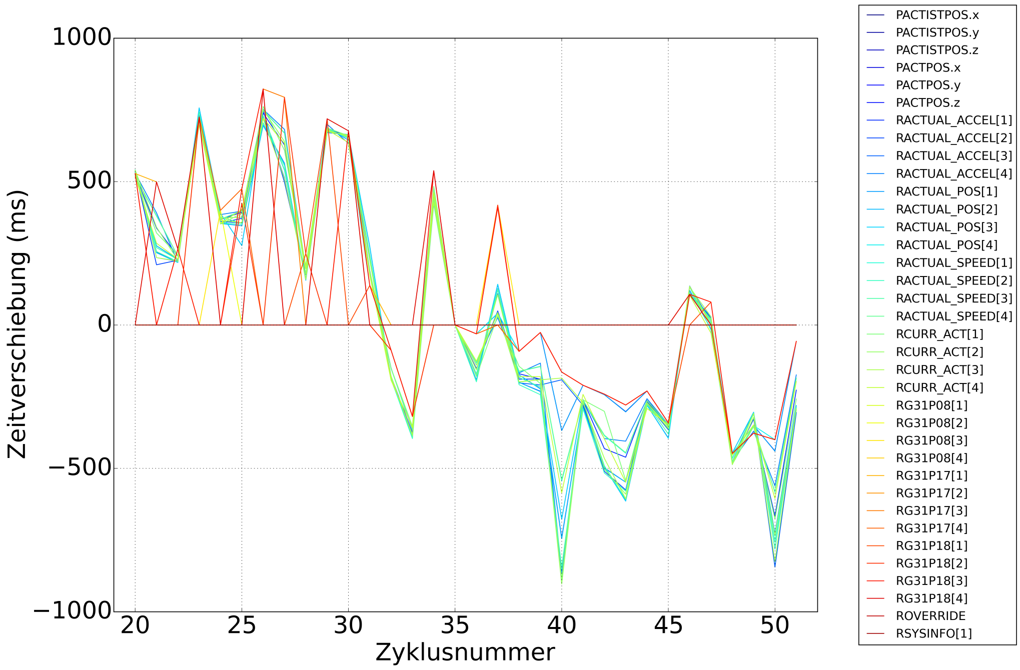


Figure 5.40: Time shift of all floating point values from cycles 20 to 52 with respect to cycle 35

5.5.5.1 Extension of TARDIS basic functionality

To ensure access to the machine data and additional needed functionality, TARDIS is extended with several modules:

- **Interval:**
  Two fixed input values are assigned to the module, which set the upper and the lower limit of the interval. Further, a third optional parameter is given as constraint, to define the step length of the interval. 1 is set as a standard value for step length. Since the function is not dependent of data beforehand, the existence of selected data can only be tested later.

- **Array:**
  To enable the selection of specific values, the String Module is utilized for arrays instead of introducing a new module. Data can be specified as comma separated values or by an interval diction (e.g. “1-10, 12-20”). Thereby, the String Module is used as a constraint and analyzed by the respective modules.

- **Plot:**
  The plot module serves as data drain and therefore has an input able to process several data sets. Besides complex depictions, the plot function also can visualize simple inputs. It was adapted to the new datasets like M-Data.

- **Log:**
  Another data drain is generated as a Log module to release single data points. The mounted input signal is passed to a textpad in the user interface to enable the display of single values.
- **Least Square Fit:**
  To control preprocessing of data in the rule editor (cf. chapter 5.5.4), a module is generated for *Least Square Fit* (see fig. 5.41). The module calculates three results for an prompted M-value, which can further be used by selection in the rule editor:

  Data A calculated time shift is determined for the first cycle of data from the M-value of the prompt. If “data” is selected as output option, indices of data are aligned with the time shift and data is returned.

  Delta T If “Delta T” is selected as output option, the respective time shift is assigned to each cycle number and returned.

  Squared Error Returns the correlation of cycle number to sum of quadratic errors for the first cycle of the transferred M-Values.

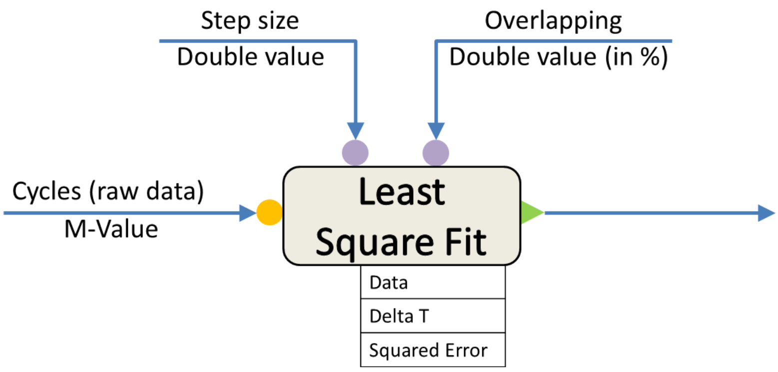


Figure 5.41: Component Least Square Fit

5.5.5.2 Use case 1: Validation of a value

Due to the robot’s movement, an expert wants to test the value of a variable, at the time point of moving at the threshold, such as the motor current. The possible over- or undershooting of the threshold value should be tested. The threshold usually is determined by expert knowledge.
The functionality of different comparisons ($<, \leq, =, \neq, >, \geq$) can already be edited without expansions in TARDIS. Figure 5.42 (l.) shows an example for use case 1 in the rule editor. On the right side, there is a graphical display for the corresponding threshold test. A single value x(t) (here: t = 5) is compared to the threshold in this figure (blue horizontal line, here: 20). The expert receives information about the relative position of the selected value versus the threshold.

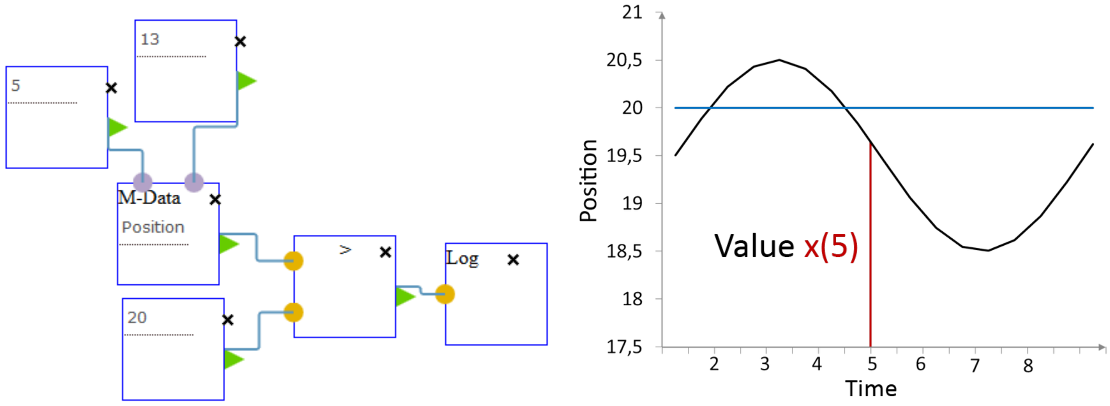


Figure 5.42: Use case 1: Example in rule editor (left) and threshold test (right)

5.5.5.3 Use case 2: Validation of a cycle

In contrast to use case 1, that tests a concrete time point, an expert does not want to be restricted to a single time point. A robot's hardware for instance is strained a lot under certain accelerations, leading to an earlier replacement or repair of parts. Therefore the expert analyzes the course of acceleration in the current cycle for a critical threshold. He can thereby locate which movements of the robot are to change to decrease strain.

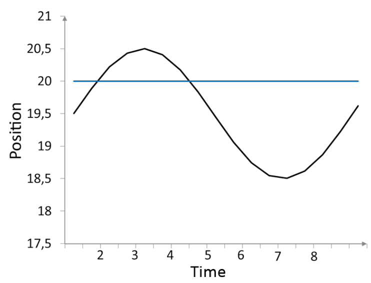


Figure 5.43: Use case 2

In use case 2 all data from one or several complete machine cycles can be analyzed for a threshold value. On the one hand, a conclusion about violation of the threshold by at least one value can be drawn. On the other hand, values exceeding or under-running the threshold can exactly be determined (cf. fig. 5.43). An expert can hence examine the relation of certain data to a critical value. With the exceeding data being returned from the function, the expert can identify the time frame of particular erroneous values.

Requirements to TARDIS The *Threshold* module was changed to occupy one input with an M-Value and a second one by a Double Value. The threshold has to react flexible, since for M-Values is not tested if data have Boolean, integer or double values. Threshold comparison between integer and double data is without difficulty. For Boolean data, a Double Value between 0 and 1 can be used. Each "True Value" for a comparative value above 0 weighs as "above threshold", the remainder counts as "below".

5.5.5.4 Use case 3: A cycle in reference to many cycles

It is important to analyze the current data course of an industry robot, particularly concerning *Condition Monitoring* (“acquisition and processing of information and data that indicate the state of a machine over time.” (ISO 13372 [140])). Analysis can be run with help of data classification. Using certain criteria, the course of data can be classified as “Okay” (O.K.) or “not Okay” (n.O.K.). The first cycles during a new robot’s operation can for instance be recorded as positive training data, as the robot lacks any signs of wear yet. Current data can be classified according to this training data. The example of position data of the robot’s axis 2 from chapter 5.5.4 is

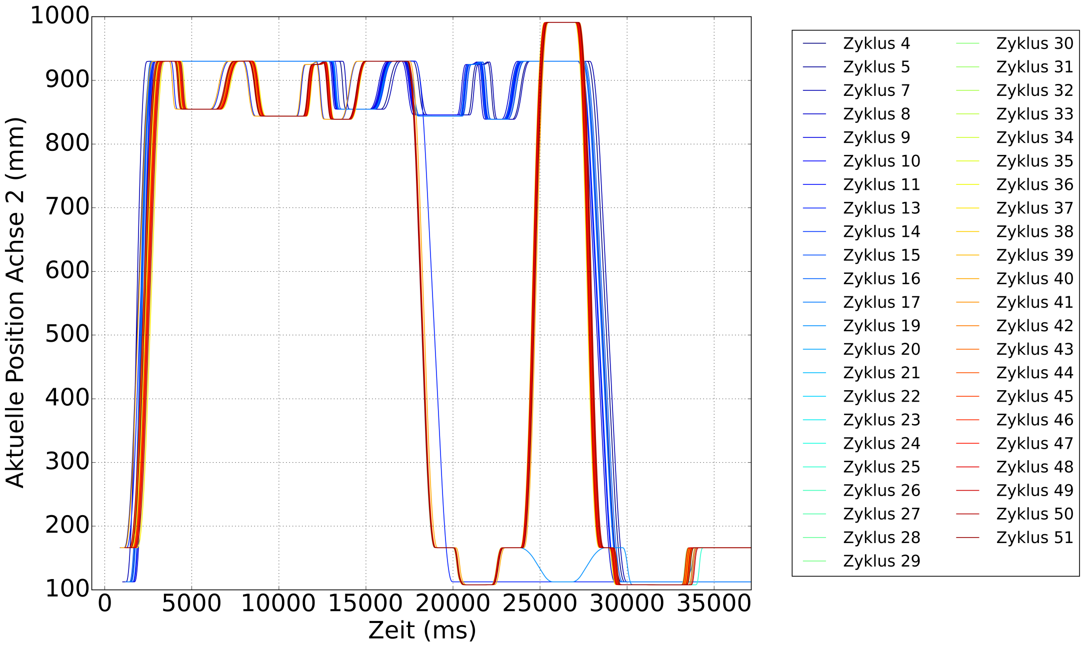


Figure 5.44: Use case 3

recharged to substantiate this. Figure 5.44 shows the course of data after minimizing the time shift using LSF. Obviously the values proceed differently. At time point 20000 msec a clear division of red and blue colored cycles can be seen. On the basis of training data the course conforming to the regular machine cycle course can be determined, and subsequently the cycles to be tested can be classified.

Requirements to TARDIS The module “Quantile Function” has to be adapted. Two M-Values are used here as input for the module, one as “current cycle” and one as “reference cycle”. It is tested initially at the outset of the function if input data types are the same. In which percentage of data the current cycle should be contained can be set as constraint. Besides the graphical output, a return value can be further used as *Binary Stream* in the rule editor. Here it is defined as a binary row of values as M-Value.

5.5.5.5 Use case 4: Visual Control

Human knowledge about the state of the industrial unit to be tested is recorded with help of Visual Control Point. Analyzing several layers of all VCPs is helpful. To determine the number of O.K. or n.O.K. classifications of a certain part of the unit, the graphical function of the histogram is employed (see fig. 5.45 (right)). An expert can easily identify the location of frequent problems in the VCPs using the added values. Likewise the VCPs with error-free classification can easily be identified.

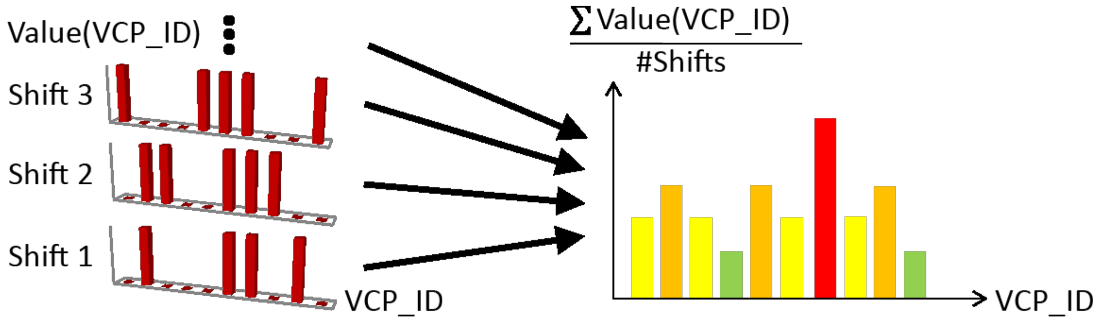


Figure 5.45: Use case 4

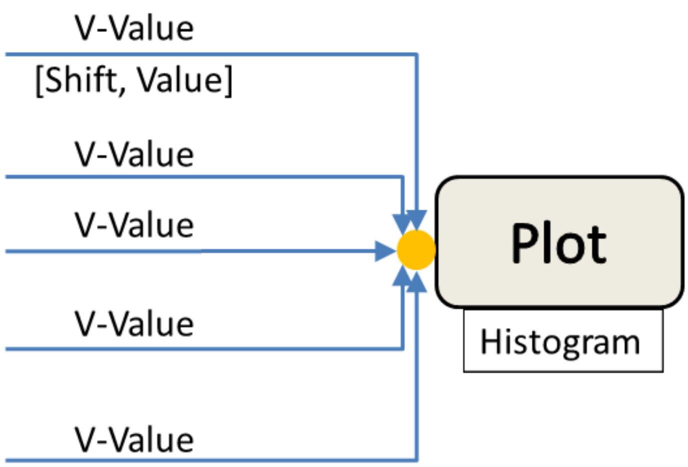


Figure 5.46: Component Plot with histogram option chosen

Requirements to TARDIS The Plot function of TARDIS is used with the option "Histogram" to attend to use case 4 (see fig. 5.46). The function is used to identify the one VCP among several, that very often or very seldom scores certain values. With help of this function can for instance be examined, if a particular machine part is erroneous, because is causes problems in many work shifts. In reverse, the correct function of machine parts or units can be ensured with the VCPs being labeled as error-free. The critically outstanding VCPs are easily visible in graphic display. An optional number of different V-Values is put into the Plot function, and can be compared to each other.

5.5.5.6 Use case 5: Correlation

A correlation matrix can be generated for several variables to trace correlations of different data. On the one hand, it allows detection of any direct influence of a variable on another. On the other hand, plausibility tests can be run to confirm the recorded data's accordance to physical laws. This can for example be used for the correlation of position and speed of a robot's axis.

Requirements to TARDIS A further selection slot "correlation" is inserted into the plot module to make the correlation matrix available in the rule editor. Moreover, a discrete number of input signals can be connected to the plot. A line and column are added to the correlation matrix for each signal, and correlation to other variables is determined.

5.5.5.7 Use case 6: Complex comparison of different cycles

After analysis of several cycles a gain in information is expected, as aforementioned. Often the analysis of certain threshold points or reconstruction of a graph is insufficient. To classify cycles according to criteria, the consideration of running several tests simultaneously seems likely. In addition to classification, also the quality of comparison between cycles can be determined and analyzed.

Requirements to TARDIS To demonstrate the combination of all functions generated for TARDIS, use case 6 is designed. Figure 5.47 illustrates an abstract situation with an expert trying to detect abnormalities in test cycles using several heuristics. Up to now, the modules *Threshold* and *Quantile Function* can be used as heuristics, but TARDIS can easily be expanded with other functions. With selection of *Binary Stream* as output of the heuristic, binary values are saved for the time points of the test cycles, informing about compliance of the heuristics. Then the binary values are evaluated using the plot function as a histogram. In the latter the number of violated heuristics and corresponding time points can be seen.

5.5.6 Results

5.5.6.1 Use case 1: Validation of a value

So-called breakpoints can be set with the AMS software. These identify time points within the robot cycle and can be determined with the robot's implementation code. **Validation of I^2T load:** The expert defines time point $t = 10s$ in the code using a robot action. At this time point the experts wants to test, if the I^2T strain lies above

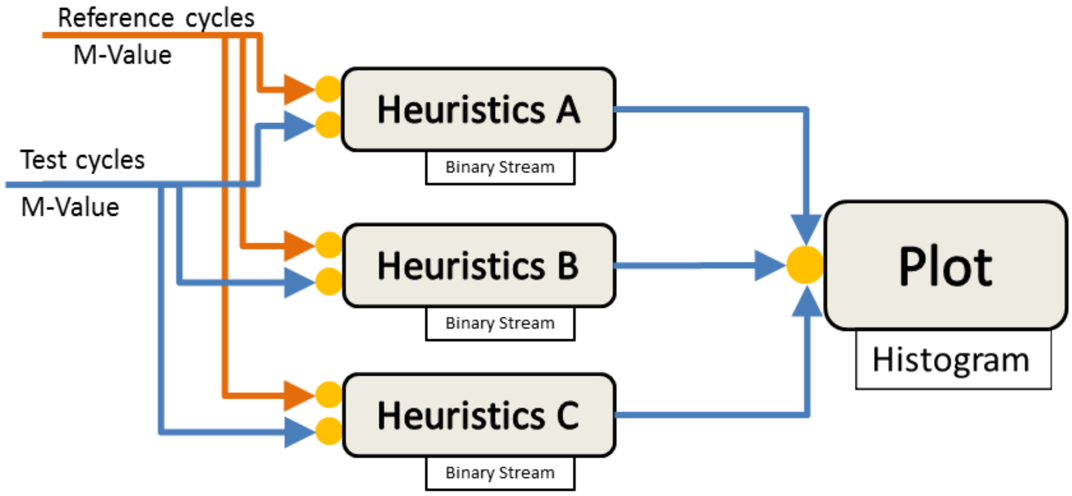


Figure 5.47: Use case 6: Comparison of many cycles with different heuristics

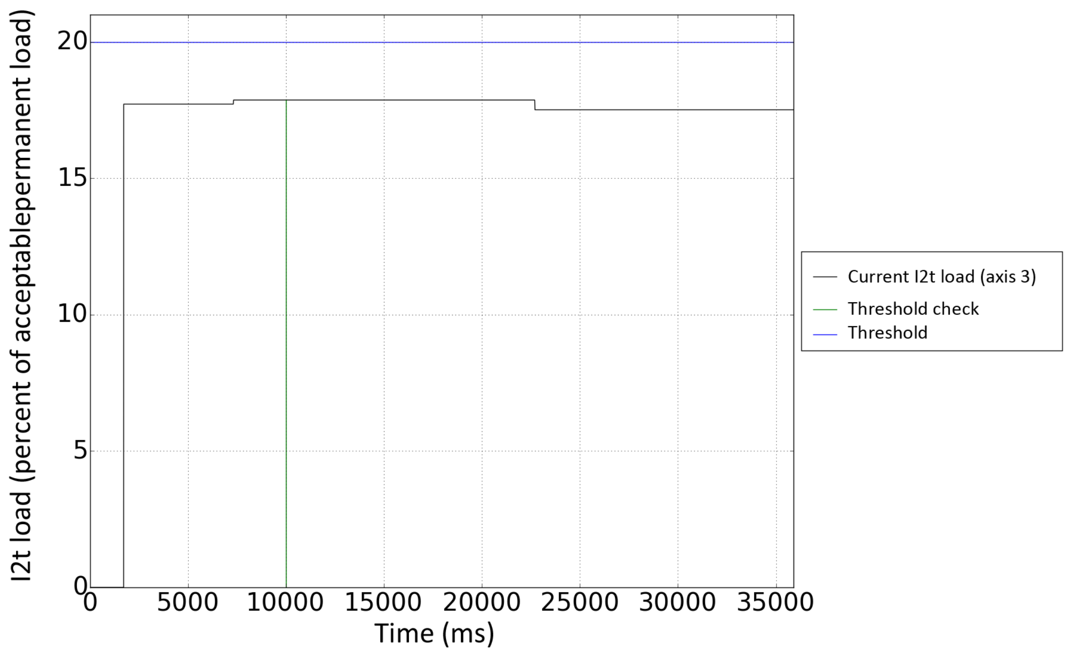


Figure 5.48: I^2T stress of axis 3 in cycle 35

the threshold of 20% of the acceptable constant strain (see fig. 5.48). Returning a `False`, the expert is informed via Log that the threshold is not exceeded at time point 10 sec. **Validation of motor temperature:** Alongside to Breakpoints,

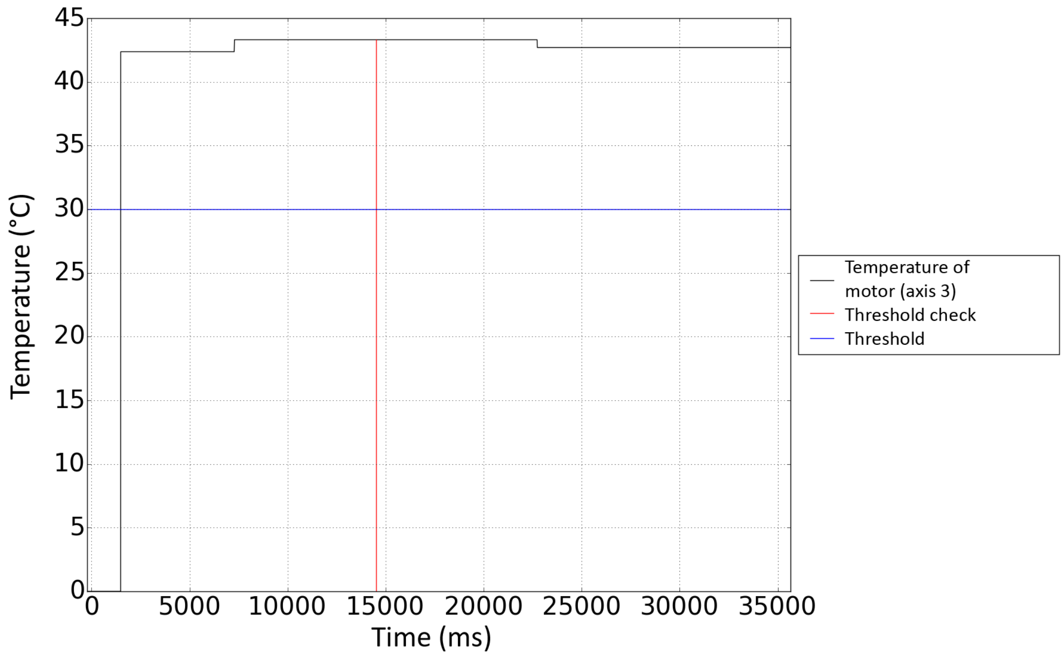


Figure 5.49: Temperature of the motor in cycle 35

the time point to test threshold values can also be determined by binary variables. Variable _IBIN_IN[3] indicates if the profiles of the injection molding machine are open. Transition from open to closed is determined at time point $t = 14,5s$. The expert tests at this time point if the motor temperature of axis 1 exceeds 30°C and receives the message `True` in the Log as a result. Contrary to the previous example, the threshold is not adhered to. Figure 5.49 exemplifies the test.

5.5.6.2 Use case 2: Validation of a cycle

Detection of current peaks: An expert wants to take a threshold test for the whole process of cycle 35 in the motor current of axis 3 (cf. fig. 5.50). The threshold of 6A to be tested is an empirical value of the expert and returns the plot seen in figure 5.51 as a result. Using the *Threshold* function in TARDIS, different return values can be employed for further modules. Thereby, the expert can, for example, illustrate only the values above the threshold, to filter out irrelevant values (fig. 5.52). **Separation of warm-up phase and regular operation:** To closer examine the course of position of axis 2, an expert wants to separate the initial cycles from the remaining cycles from a dataset. He applies the Least Square Fit function to gain a heuristic stating which cycles do not fit into the normal process (cf. fig. 5.53). For each cycle the sum of the quadratic errors to the reference cycle

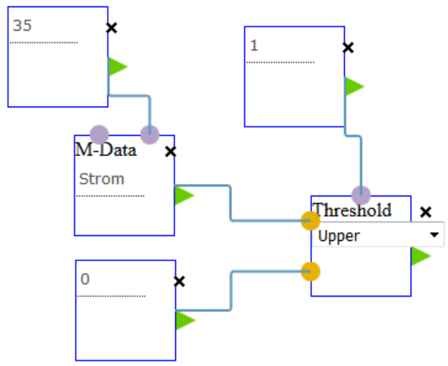


Figure 5.50: Rule example for detection of current peaks in the rule editor

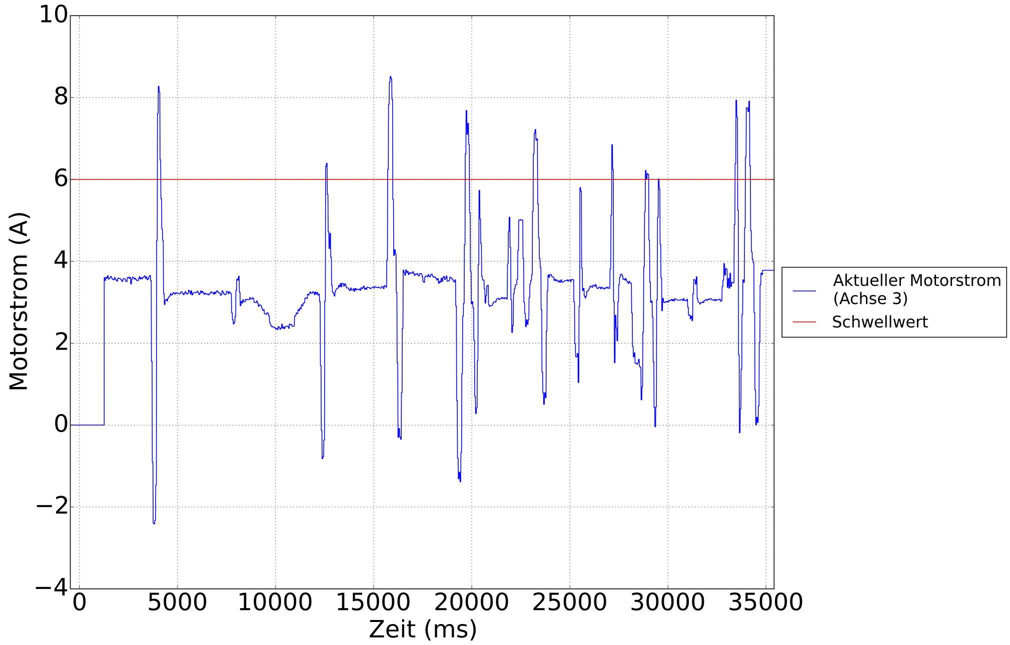


Figure 5.51: Current of the motor of axis 3 over time

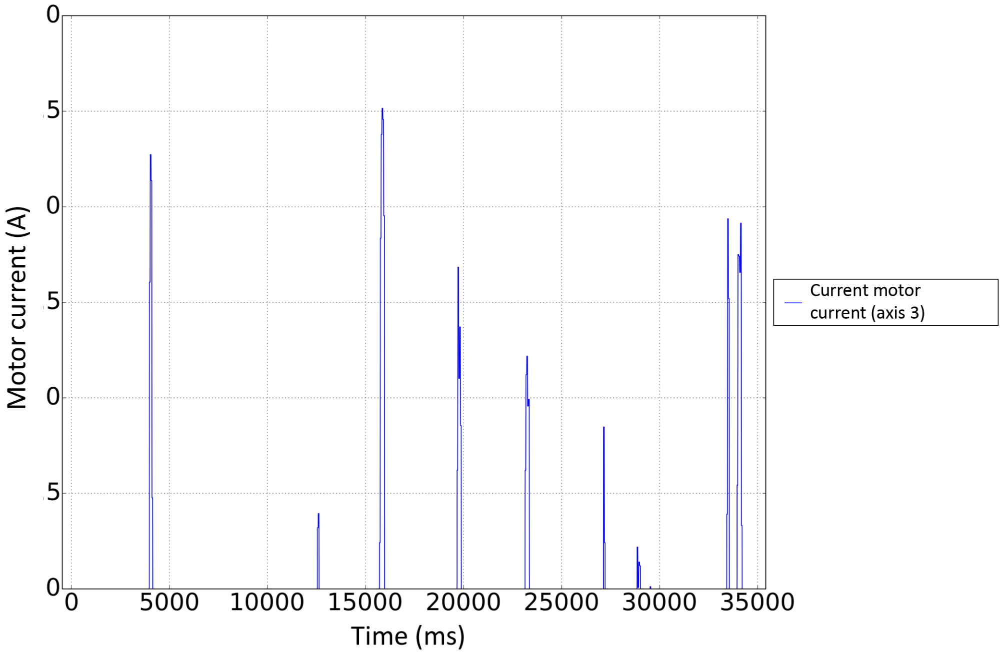


Figure 5.52: Current of the motor of axis 3 is above the threshold 6A

(here cycle 35) is identified by the LSF. On base of the display of quadratic errors (see fig. 5.54), the experts chooses a threshold (here: $5 \cdot 10^8 \mathrm{mm}^2$), above which cycles are not classified as operating phase.

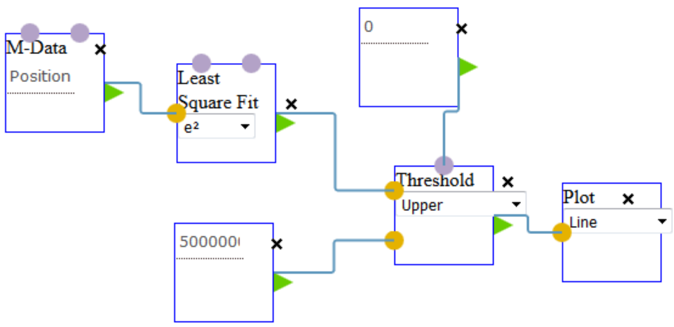


Figure 5.53: Example rule for separation of warm-up phase and regular operation in the rule editor

5.5.6.3 Use case 3: A cycle in reference to many cycles

Testing the acceleration (axis 4) of cycle 40: When separating initial and operating phases (section 5.5.6.2), the expert notices by the sum of quadratic errors, that cycle 40 also shows a high deviation when compared to cycle 35 (cf. fig. 5.54). First the experts decides to use cycles 19 to 52 as training data. That means that

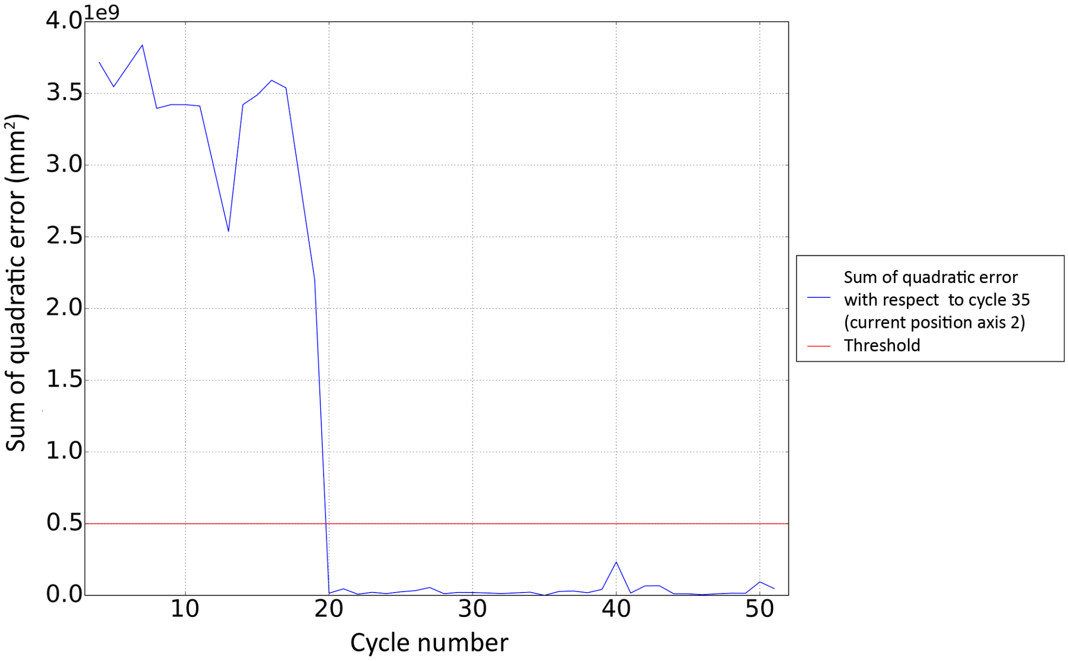


Figure 5.54: Sum of the quadratic error to cycle 35 of the position values of axis 2

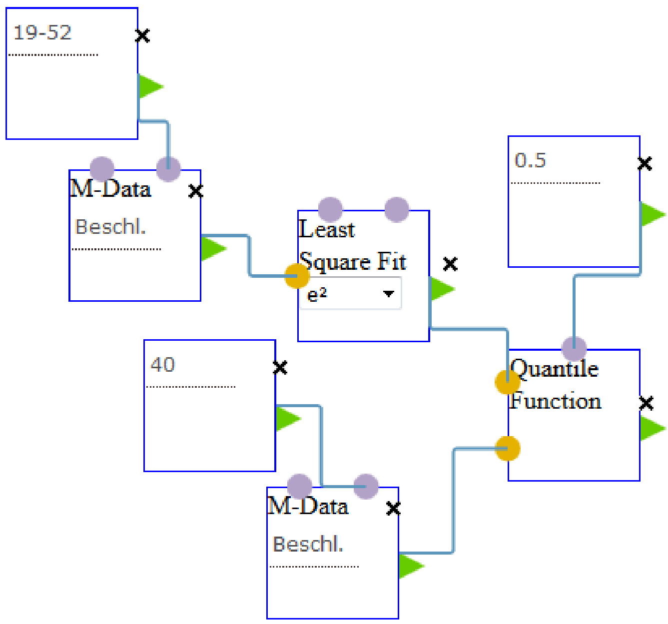


Figure 5.55: Example rule for testing the acceleration (axis 4) of cycle 40 in the rule editor

the training data is classified as “following the usual process” (or “O.K.”). The expert compares the training data with cycle 40 to accelerate axis 4 using *Quantile Function* from the rule editor (cf. fig. 5.55). At first, the level of deviation is tested for a share of 50% of all training data (fig. 5.56). A part of figure 5.56 is magnified in figure 5.57 for better comprehension of the generated graphic. Figures show training data (reference cycles) in light gray and the consequential quantile area in dark gray. The course of cycle 40 is colored in black, as long as it is inside the quantile area. Values lying outside are indicated in red. In figure 5.56, the reason for cycle deviation can barely be seen, because the bigger part of cycle 40 does not correspond to the quantile area, thus coloring a wide area in red. The expert decides to test cycle 40 for 100% of all training data (fig. 5.58). Especially the deviations in the two strong accelerations at approximately 3 and 17 seconds strike at this point. In the first acceleration, deviations are left, whereas they are on the right side for the second acceleration. That implies that the first acceleration of cycle 40 starts earlier, and the second later.
Temperature range of the controller power stage: Additionally to cycle testing, *Quantile Function* can also be used to identify the data range. Therefore identifying the maximal and minimal range is beneficial for hardly comparable data, such as temperature courses.
Figure 5.59 illustrates the temperature range of the modulator’s power stage on axis 4 for all 52 cycles. Minimal values are displayed as blue lines, maximal values in green. Contrary to the previous requirements, reference cycles are drawn here in the foreground. This helps to distinguish data referring to the quantile area.

TARDIS implementation M-Data’s structure (cf. chapter 5.5.3.1) allows to transfer both “reference cycles” as well as “current cycle” with optional constraints to the *Quantile Function* (cf. section 5.5.5.4). In general, M-Value indicates any number of cycles which are labeled with [timepoint, value] pairs. This improves the handling of rule editing, rather than transferring each individual reference cycle to *Quantile Function*.
Functionality of *Quantile Function* is not limited by time points or cycle number, meaning that any cycle number can be indicated. An expert can thus for instance specify various cycles as current and test these for a reference cycle. This would presumably lead to many deviations, but is the user’s decision. Likewise, input parameters can be chosen for single time points. This makes sense when only certain time spans are being observed with corresponding data being tested. The result of *Quantile Function* generally strongly depends on input data. The case of M-Value entries including binary values is not sensible for the *Quantile Function*.

Python implementation To gain a reasonable comparison between reference cycles and the current cycle, *Quantile Function* has to run a Least Square Fit prior to all calculations, like in data preprocessing (chapter 5.5.4). For the “current cycle” (or an optional number of these), temporal deviation from one of the reference cycles is determined by LSF. As a “good order” of all training data cycle is assumed, the

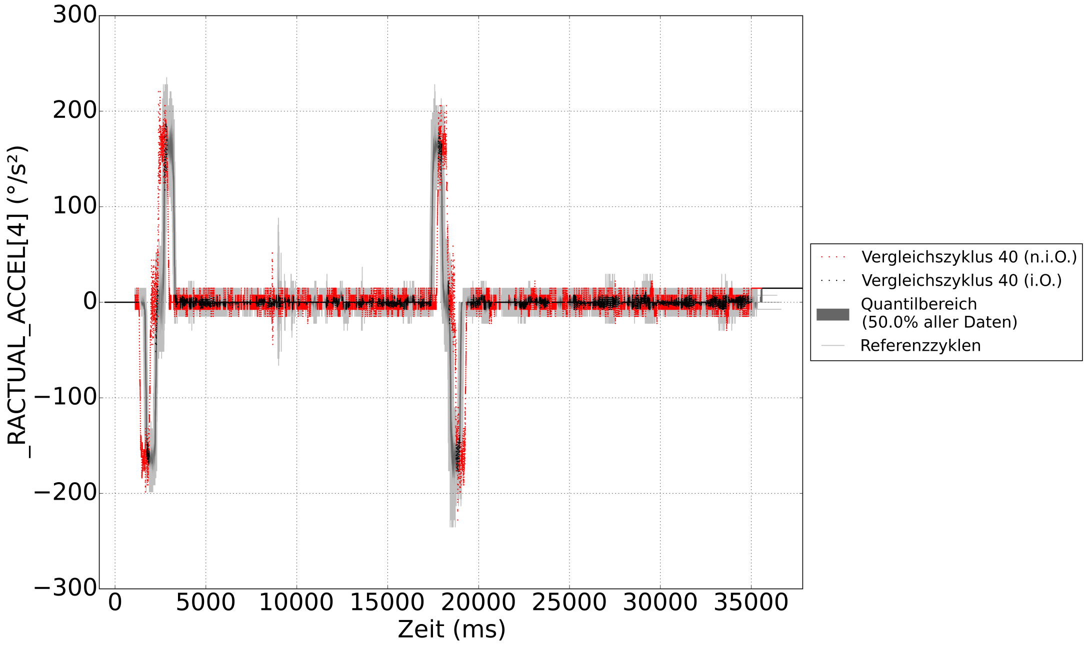


Figure 5.56: Acceleration of axis 4 (50% Quantile)

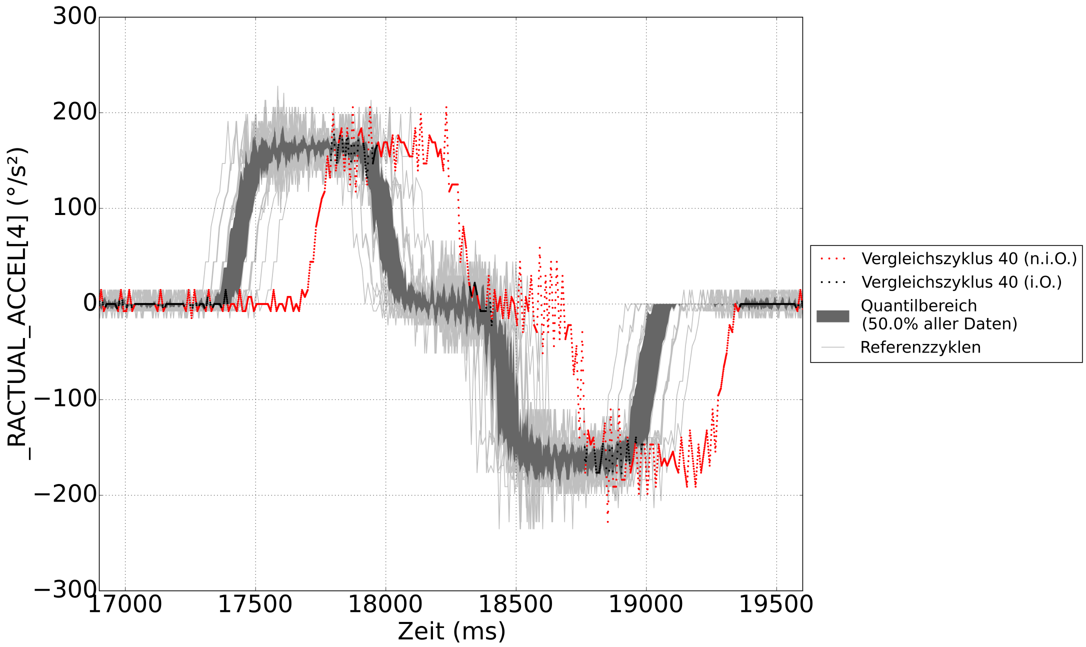


Figure 5.57: Acceleration of axis 4 (50% Quantile, zoomed)

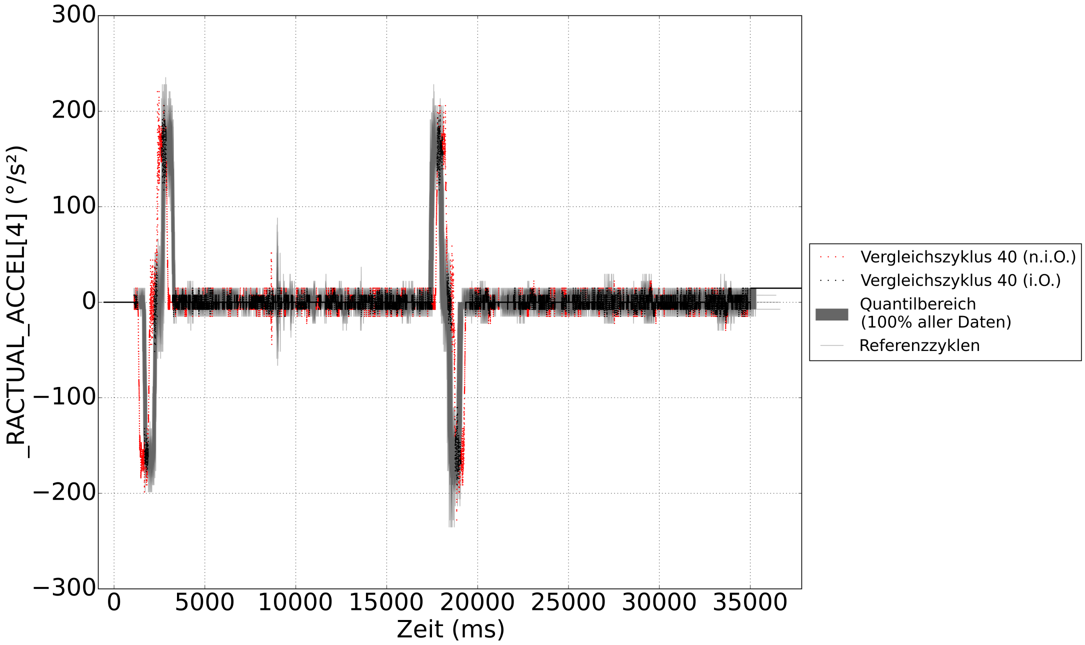


Figure 5.58: Acceleration of axis 4 (100% Quantile)

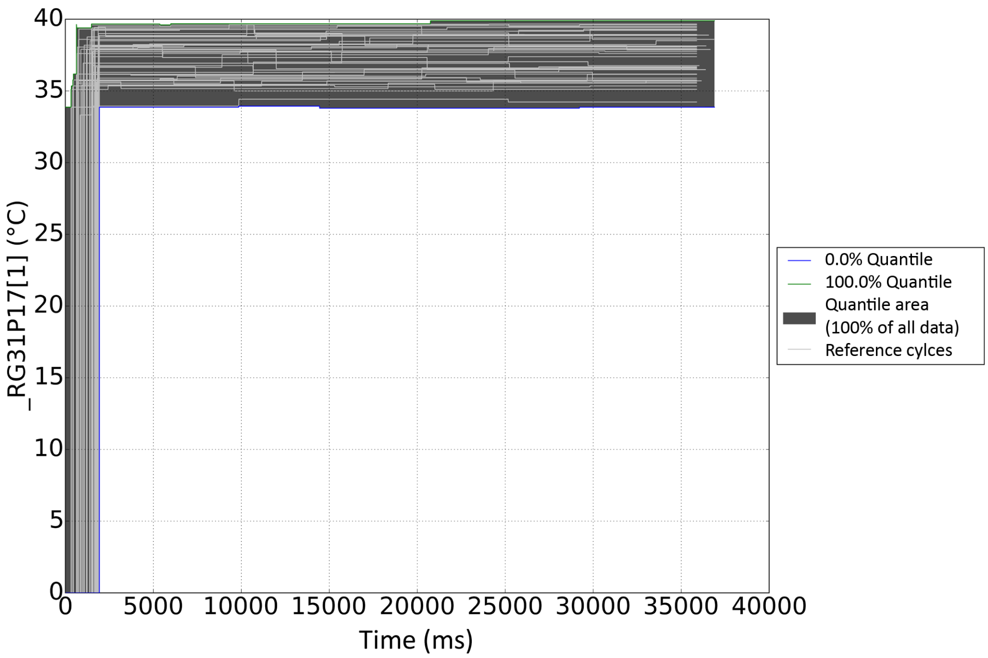


Figure 5.59: Temperature range of the controller power stage

first reference cycle is selected as compensating curve for LSF.

5.5.6.4 Use case 4: Visual Control

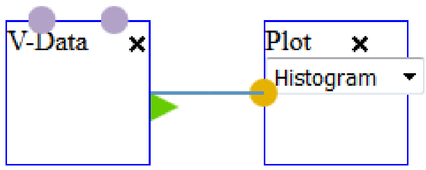


Figure 5.60: Rule example for creating a histogram of all VCP data

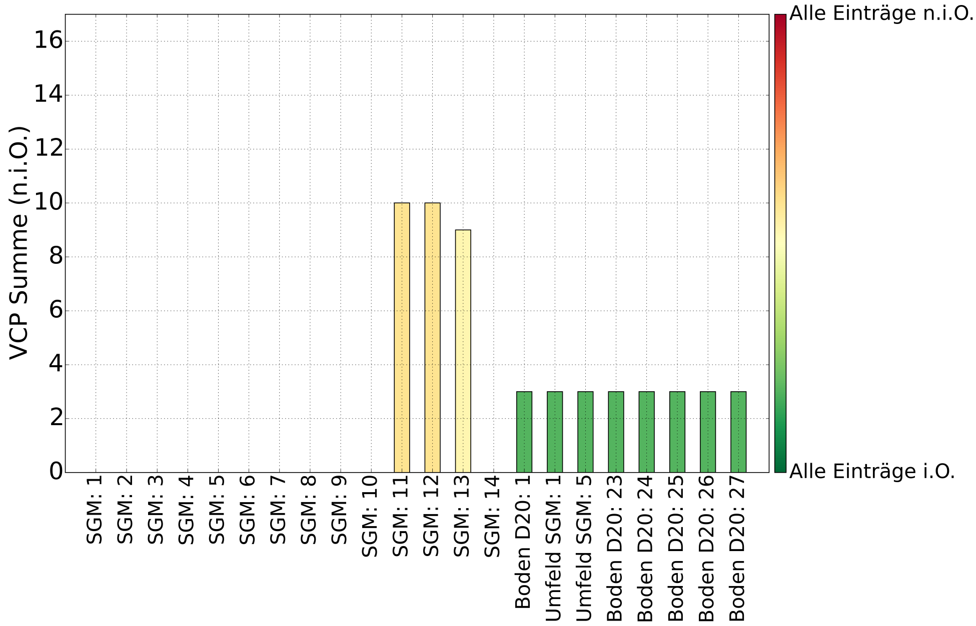


Figure 5.61: Plot of the VCP histogram

To analyze the technicians' rating of each Visual Control Point in several layers, from all VCPs a histogram is generated over several layers. A color spectrum is used for chromatic visualization of evaluation, from red (VCP in all layers “not O.K.”), through yellow to green (VCP in all layers “O.K.”). Figure 5.61 shows the result generated in the rule editor (see rule from fig. 5.60). The result reveals that many VCPs in the SGM area are labeled “O.K.” in the 17 tested layers. Testing points “SGM: 11”, “SGM: 12”, and “SGM: 13” on the injection molding machine show the most “n.O.K.”-labels. Remaining VCPs were marked respectively three times as “n.O.K.” by the technicians.

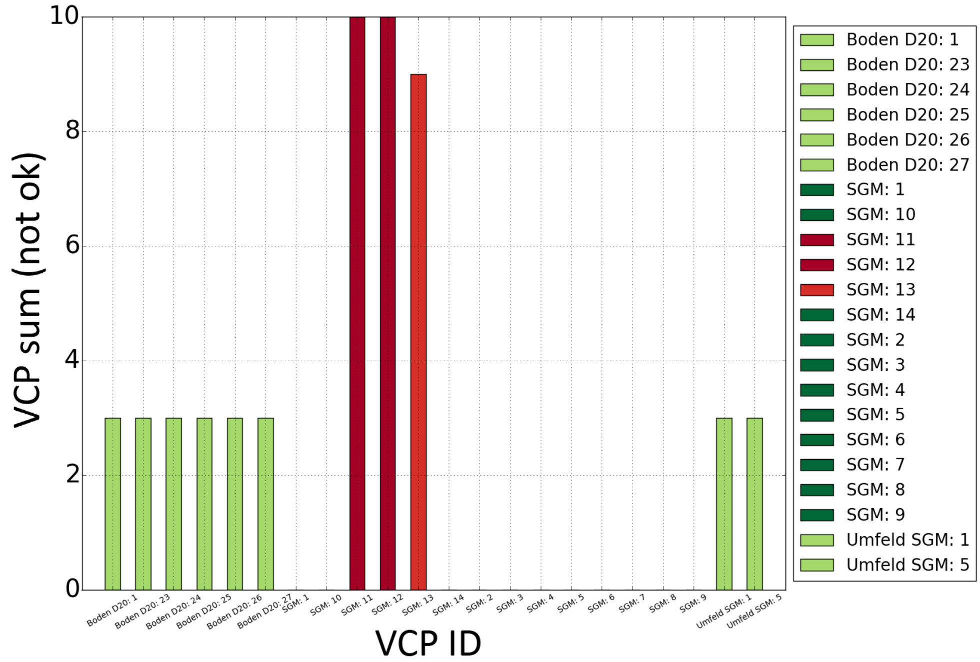


Figure 5.62: First draft of plotting the VCP values

Python implementation V-Value describes binary values of a VCP, assigned to a correspondent working layer (cf. chapter 5.5.3.2). In Python VCPs are managed as an index of a *DataFrames* (cf. section 5.5.2). The VCP's value in column “Status_sum” is incremented for each “n.O.K.” entry. In the result this value is implemented as bar height. Figure 5.62 shows an early version of visualization. In this version the VCPs are mentioned in the caption as well as in the 45° angle of the abscissa. Apparently the labels on the abscissa appear shifted. *matplotlib* centers captions under the respective point on the abscissa by default setting. Due to the rotation, correlation to the middle part of graphic is almost impractical for the reader. Therefore, a rotation of 90° is selected for labeling the abscissa. The display in figure 5.62 implies that VCPs SGM: 11 bis 13 are n.O.K. in all layers, since the ordinate scale is not shown up to the full number of layers. Given that this is not true, the ordinate maximum is set to the total number of layers.

5.5.6.5 Use case 5: Correlation

To specify correlation of position, speed, acceleration, and motor current of the robot's axis 2, an expert generates a correlation matrix with help of the plot function (see figure 5.63). Relations between the variables can hardly be seen therein, prompting the expert to examine parts of the matrix separately in the subsequent applications.

Plausibility test on position and velocity: A plausibility test is run as a practical use case for data correlation. The expert wants to test whether the formula

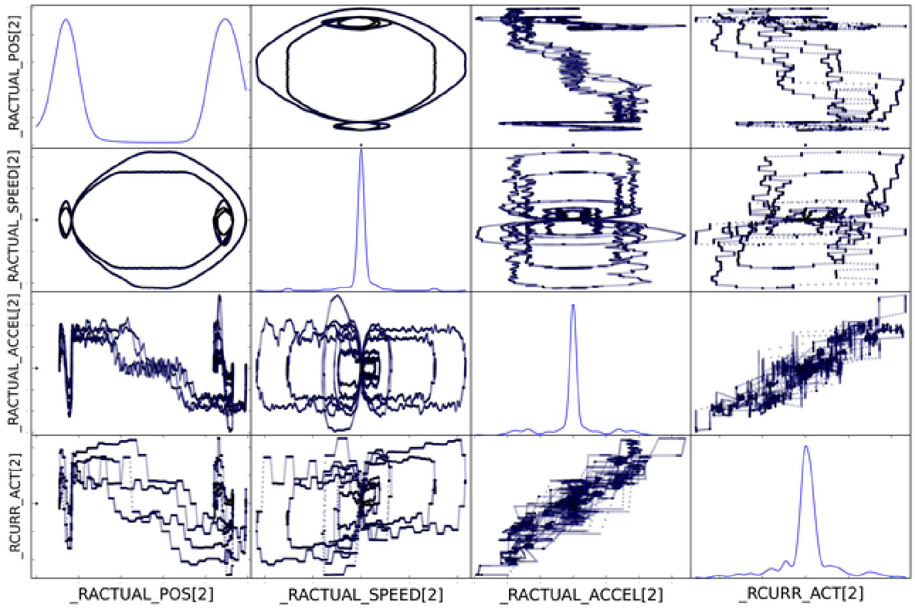


Figure 5.63: Correlation between position, velocity, acceleration and motor current of axis 2

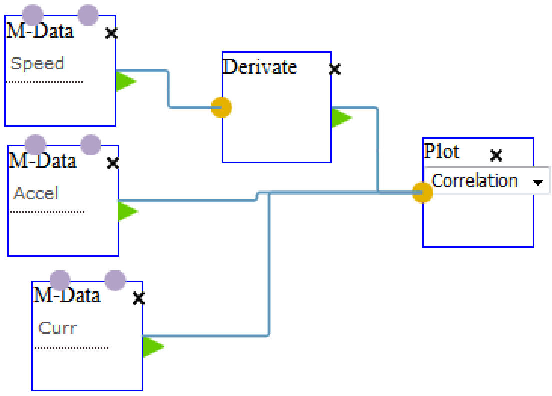


Figure 5.64: Example rule for correlation of velocity, acceleration and motor current in the rule editor

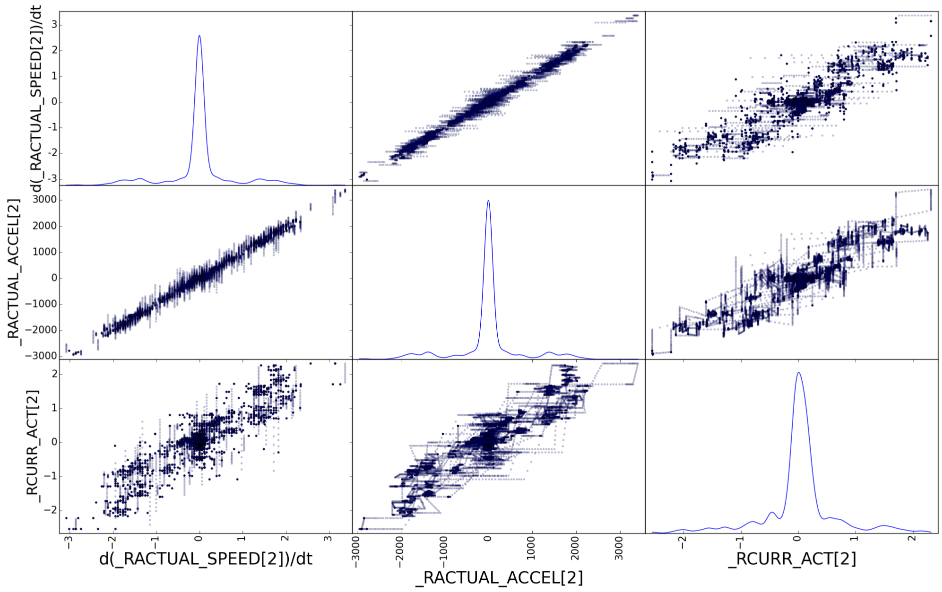


Figure 5.65: Correlation of velocity derivation, acceleration and current of axis 2

$v = \frac{d}{dt}x$ is valid for axis 2 of the robot. Thus he tests, if the derivation of position data (x, _RACTUAL_POS[2]) is positively correlated with the measured speed data (v, _RACTUAL_SPEED[2]) at the time (t). He designs the rule from figure 5.64 using the rule editor. The plot function delivers figure 5.65 as a result. The expert's hypothesis is confirmed by the clearly positive correlation of both variables.

Plausibility test on velocity, acceleration and motor current: The expert wants to detect a correlation of speed (v, _RACTUAL_SPEED[2]) and acceleration (a, _RACTUAL_ACCEL[2]) of the robot's axis 2 in measured data. Demonstrating the correlation demands the derivation of speed to time (t) ($a = \frac{d}{dt}v$). In addition the experts investigates if the motor current (_RCURR_ACT[2]) of axis 2 correlates with acceleration of axis 2. Data is sent to the plot function by TARDIS (see figure 5.64). Obviously all three variable correlate positively. Thereby the connection of acceleration and speed of the robot's axis 2 is verified. Furthermore it is visible that the correlations between motor current and both other variables roughly meet a positive linear slope.

TARDIS implementation Since the derivation of variables is a crucial part for the requirements of use case 5, the rule editor has to offer a `Derivate` function. The function has exactly one input and one output signal and provides the input deviation according to the index variable. I.e., a data structure manageable as `DataFrame` is assumed to ensure a smooth execution of the derivation by the *pandas* library (cf. chapter 5.5.2).

Further, the selection "Correlation" is added for realization in the plot function.

Python implementation The `pandas` library uses functions of the `matplotlib` library for graphic display. With the correlation matrix being a composition of several plots from `matplotlib`, `pandas` offers a pre-assembled function to generate the correlation matrix from a `DataFrame`. From the linear interpolation of data

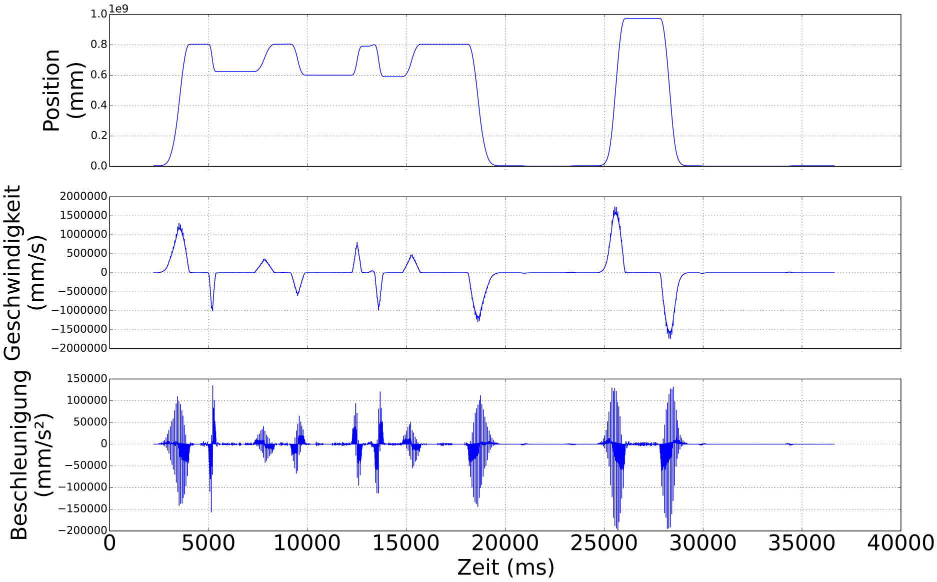


Figure 5.66: Top to bottom: linear interpolation of the position of axis 2, first derivation of position with respect to time, second derivation of position with respect to time

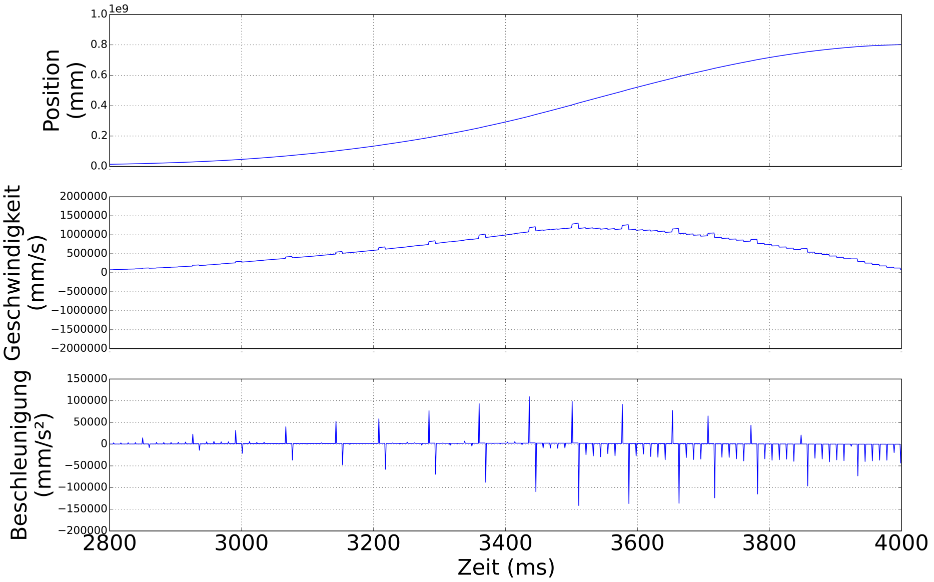


Figure 5.67: Top to bottom: linear interpolation of the position of axis 2, first derivation of position with respect to time, second derivation of position with respect to time

in preprocessing, the derivations produce imprecise results after some time. As an example, in figure 5.66 the first two derivations of position to time are illustrated for the position of the robot's axis 2. In figure 5.67 the display of the time sector between 2.8 and 4.0 seconds is magnified. This clearly shows interpolation errors already had occurred during the first derivation. It is hence not possible to give a realistic statement for the correlation of derived variables.

5.5.6.6 Scenario 6: Complex cycle comparison

Application Comparing cycle 40 to certain reference cycles regarding the acceleration of axis 4 does not suffice for the expert. He wants to examine for various variables, at which time points there are deviations from the 100% area of the reference cycles.

Figure 5.68 depicts the rule to be analyzed by the expert. He uses two times four M-Data modules, equivalent to position, speed, acceleration and motor current of axis 2. One M-date symbolizes cycle 40, the second one is utilized for the reference cycles of the same variable (here cycles 19 to 52, except cycle 40). Time deviations of reference cycles from the database must initially be corrected via the LSF function. Then *Quantile Function* is run according to the respective variable, and the result is transferred to the plot function as a *Binary Stream.* The result of this rule is seen in figure 5.69.

The number of heuristics, in which cycle 40 deviates from training data is determined for each time point. Since altogether four heuristics are employed, cycle 40 can at most derive from four heuristics. Figure 5.69 exhibits that cycle 40 in some phases differs from all of the heuristics. But still there are time points with data from cycle 40 residing within the 100% quantile area of training data for all heuristics. This is for instance seen from time point at 34 seconds.

Python implementation With Python's extreme flexibility when working with data types, there are no problems to edit data consecutively with various functions. For this scenario, four variables of cycle 40 are tested for the respective 100% area of reference cycles. Employment of different parts of reference cycles with the Quantile Function regarding the same variable implies a correlation of results, and thereby falsifies the result in histogram display. Thus the Quantile Function should only be used independently from each other, when giving different percentages regarding a single variable.

5.6 Generating hypothesis and corresponding rules from sample data

5.6.1 Motivation

Sometimes it is hard for non-technical personnel to formulate adequate rules that describe the wanted behavior well. One reason is that the medical personnel isn't familiar with this type of structured thinking so they can't transform their knowledge

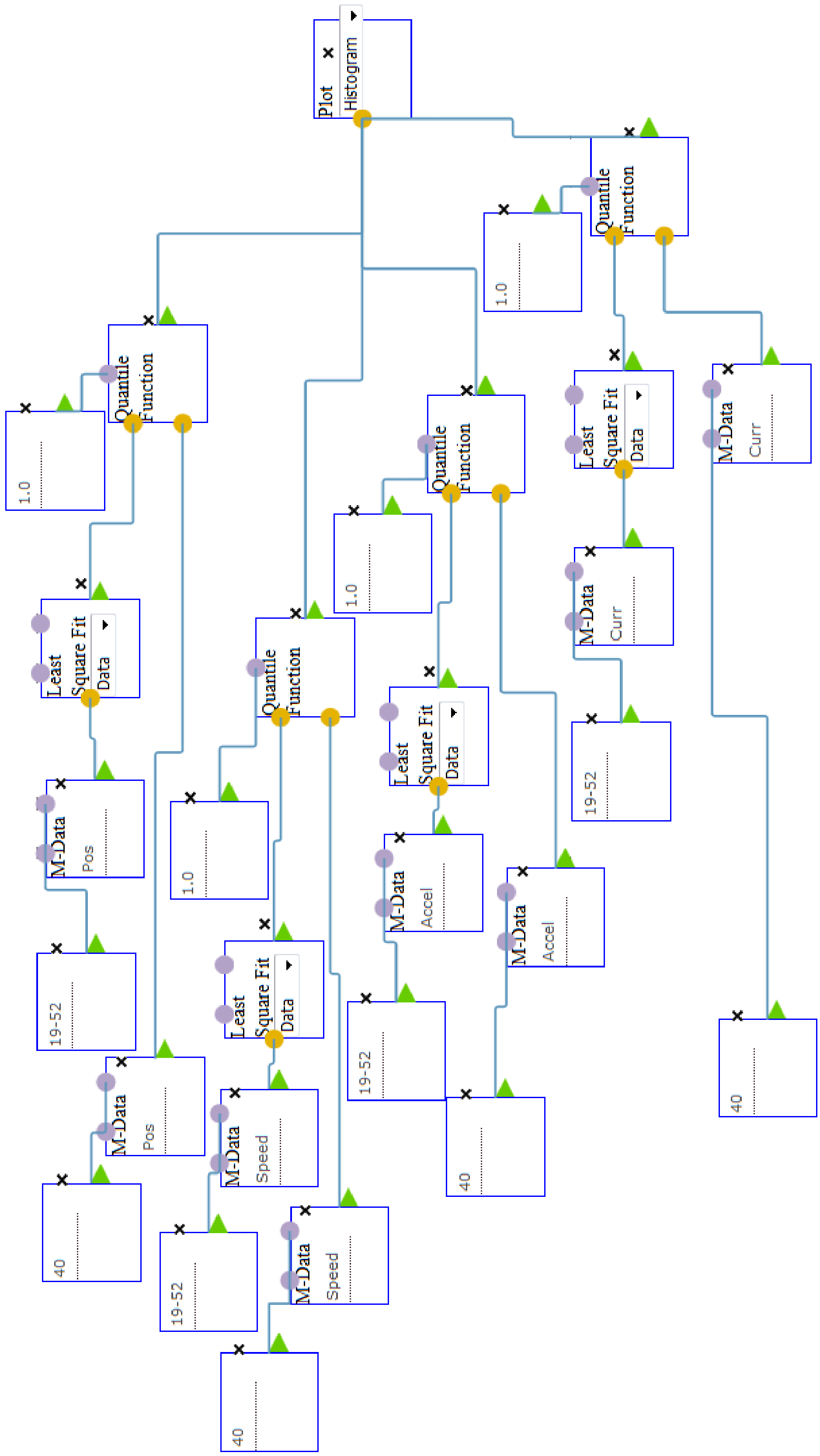


Figure 5.68: Example of a rule for creating a histogram of several *Binary Streams* in rule editor

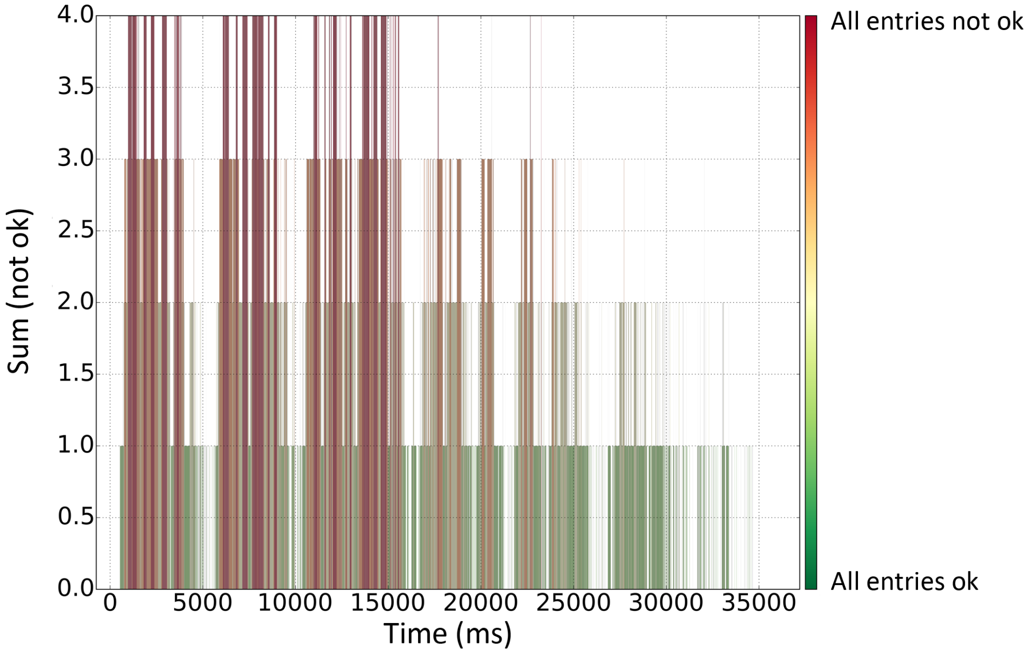


Figure 5.69: Validation of cycle 40 with four different heuristics

into the needed structure of boolean rules. But even when they are assisted at translating the rules in their head into the "mechanical type" they struggle to form the rules. A lot of medical knowledge is kind of fuzzy and based on experiences. Even if the experts follow specific rules to assess situations or patients often these rules are purposely available for the experts. The last chapter showed that good rules can help a lot at filtering and sorting the massive amount of data which leads to a reduction of workload for the users. So how do we get rules that are helpful when the experts, that hold the knowledge, aren't able to create the rules themselves?

The system itself can use data mining and analysis algorithms to search for patterns in the incoming data of the patients. If a possible rule is found it is presented to the experts for validation and evaluation. This procedure can generate rules, the medical experts are not able to formulate. It also has the potential to find new correlations in the medical data that are yet unknown to the experts. We tested the feasibility of this approach by processing our patient data in two different use cases.

5.6.2 Goals

We want to use the incoming data to improve our data analysis. The existing rulesets should be extended to provide better predictions of the patients health status and current or upcoming events. Eventually new correlation in the data can be found by computer-generated rules. We use data-mining and machine learning algorithms to extract knowledge out of the data and generate rules that may offer a benefit to the user. The generated rules are then presented to the user of the system to be evaluated and accepted. In this work the generated rules are not automatically rated for their correctness, usefulness or meaningfulness. The expert has to decide if the rule should be used to analyze future data sets.

5.6.3 COPD - Desaturation events during night

Patients that suffer from COPD are facing oxygen desaturation events during sleep times. This can be dangerous when the desaturation events happen too often or too long because it can lead to insufficient oxygen levels in the blood which means that organs can be damaged. When COPD patients are monitored during sleep the oxygen desaturation events are closely analyzed. The data is normally viewed and analyzed in specialized software. An example of the large amount of data that is recorded during one measurement is displayed in figure 5.70 where it is shown in such a viewing and analysis software. In our home monitoring scenario (see chapter 4.2.2) these data would be transmitted from the patients home to the telemedical center. The medical personnel wants automatic analysis and summary of the data, so that critical patients pop out and are identified very fast. A rule for the automatic detection of desaturation events in the data would help there.

5.6.3.1 Example data

We got some data from a sleep laboratory where COPD patients are monitored during sleep. The measurements contain very much data from up to 29 different sensors. The dataset we used for our tests consist of 22 sensors that generated 28 different parameters that were measured in fixed frequencies. Table 5.1 lists the measured parameters together with their corresponding measuring frequencies.

5.6.3.2 Learning process

The analysis of the data is done in Rapidminer [142], a software for data mining and machine learning. Figure 5.71 shows the learning process in Rapidminer. The training data is stored in individual files for each sensor. Therefore we have several "lanes" that import and preprocess the data from the different sensors before they are joined. The leftmost block in each lane imports the training data. The preprocessing part begins with a conversion of the timestamps for all records. Afterwards the attributes for the learning process are selected. The continuous data is already sampled by the sensors and their data acquisition and storage systems. Since the sampling rate of the sensors differ, there would be a lot of missing values when all the records are combined with respect to the timestamps. To avoid that we added a further binning step (the “Aggregate” block), that uses the average sensor values of a defined time slot. We used time slots of 5 seconds in our example. The following steps are the preparation for joining the separate data and the joining itself. Afterwards, missing values in the target attribute are complemented. The recorded data of our target attribute contains the time slots where desaturation

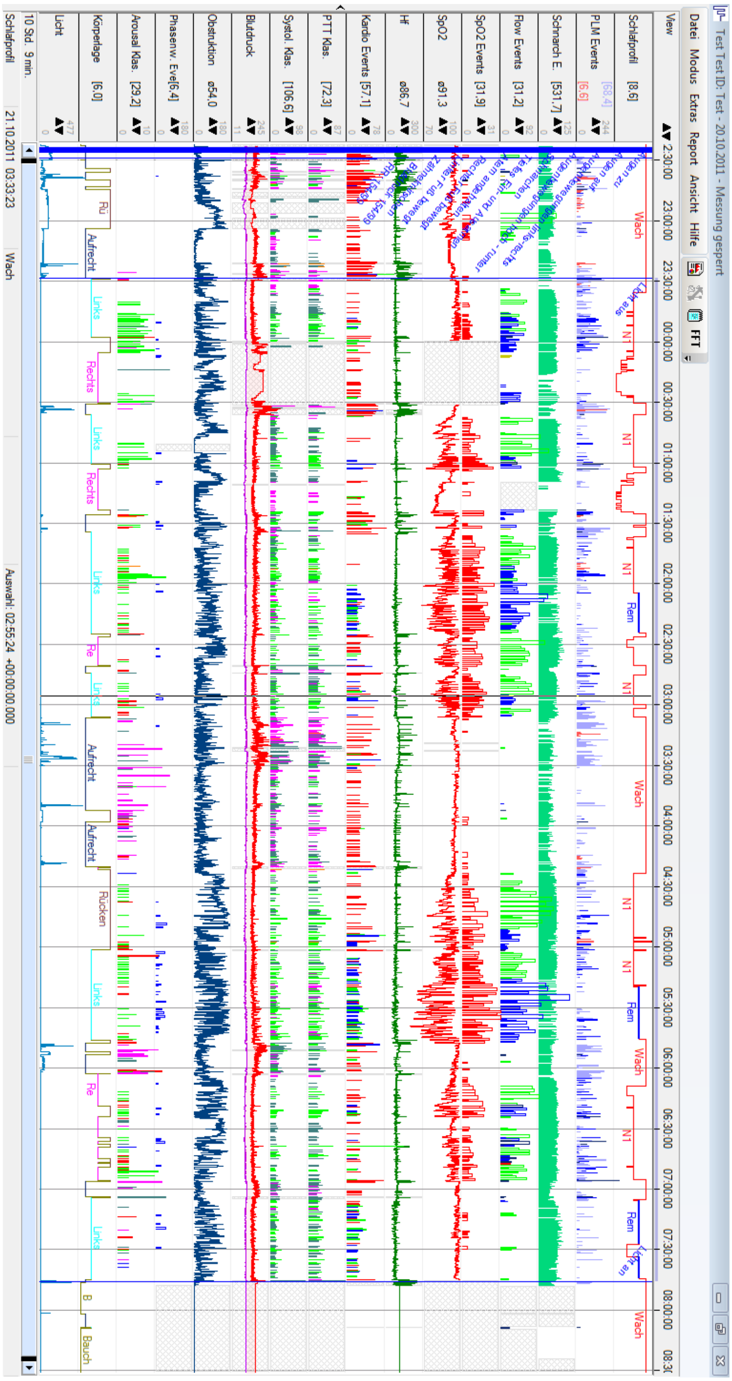


Figure 5.70: Viewing the captured data of a patient in a specialized analysis software (Somnomedics Domino [141])

Table 5.1: Parameters that are recorded during sleep time of a COPD patient

Name	Unit	Type	Interval (Hz)
RR Interval	ms	analog	256
AmvD	L/min	analog	1/3
AzvD	ml	analog	1/3
Activity	mg	analog	32
Phase angle	degree	analog	1
PTT raw	ms	analog	128
Diastol PTT	ms	analog	128
Systol PTT	ms	analog	128
SVB	LF/HF x10	analog	1/4
HRV VLF	ms x0.1 RMS	analog	1/4
HRV VHF	ms x0.1 RMS	analog	1/4
Breathing frequency	/min	discrete	256
EMG	dB	analog	256
SchlafFFT/Sigma	µV	analog	1
SchlafFFT/Delta	%	analog	1
SchlafFFT/Alpha_Beta	%	analog	1
SchlafFFT/AFV	Hz	analog	1
Sleep profile certainty		discrete	1/30
Light	lux	analog	4
Position		discrete	4
Obstruction	degree	analog	1
RR Diastol	mm Hg	analog	128
MAD	mm Hg	analog	128
RR Systol	mm Hg	analog	128
Heart frequency	bpm	analog	4
SpO2	%	analog	4
Sleep profile		discrete	1/30

events occurred. The missing values represent time slots where no desaturation was detected. Finally the joined data is fed into the decision tree algorithm.

5.6.3.3 Results

The resulting tree for this use case is very large. Figure 5.72 shows one weakness of the decision tree algorithm: when the training data contains attributes that can assume a lot of different values, the resulting tree can get very broad. Our training data contains mostly continuous measured values hence the tree splits on many values that differ not much from each other.

If we transform the tree into a rule for our framework, the rules would be likewise complex and broad. We decided to use the result in a function that marks areas, that correspond to the rules, in the data. This results in a visualization of desaturation events that can be easily detected by the human supervisors. Figure 5.73 shows a comparison between the desaturation events listed in the training data (marked in red) and the markings made by the function that was generated (marked in green). Our function does not mark all of the desaturation events so the parameters of the learning algorithm could be tweaked to achieve a higher accuracy of the marking function.

5.6.4 Intensive care - Relocation of critical patients

In our intensive care scenario, described in chapter 2.2.3, the experts have to decide very fast whether a patient has to be transferred to the specialized center for further treatment. Also the appropriate transportation method (intensive transport or helicopter) has to be chosen. Since most of the patients suffer from a injury of the lung, the severity of the acute respiratory distress syndrome (ARDS) can be an indicator if and how the patient has to be transported. The severity of ARDS is divided into four categories: none, mild, moderate and severe, according to the Horowitz index which is defined as the ratio of the partial pressure of oxygen in the blood (PaO2) and the fraction of oxygen in the inhaled air (FIO2) [143].

5.6.4.1 Example data

We used the data of the transferred questionnaires from the past 4.5 years to train the algorithms. That is an overall amount of 180 records consisting of up to 118 parameters for each record. Some of the parameters are already calculated scores that describe the state of the patient. These parameters were left out in the training data. We used the Horowitz index as the target classification we want to find rules for.

5.6.4.2 Learning process

Figure 5.74 shows the modeled process in Rapidminer for analyzing the training data. The leftmost block imports the training data. Then the target classification

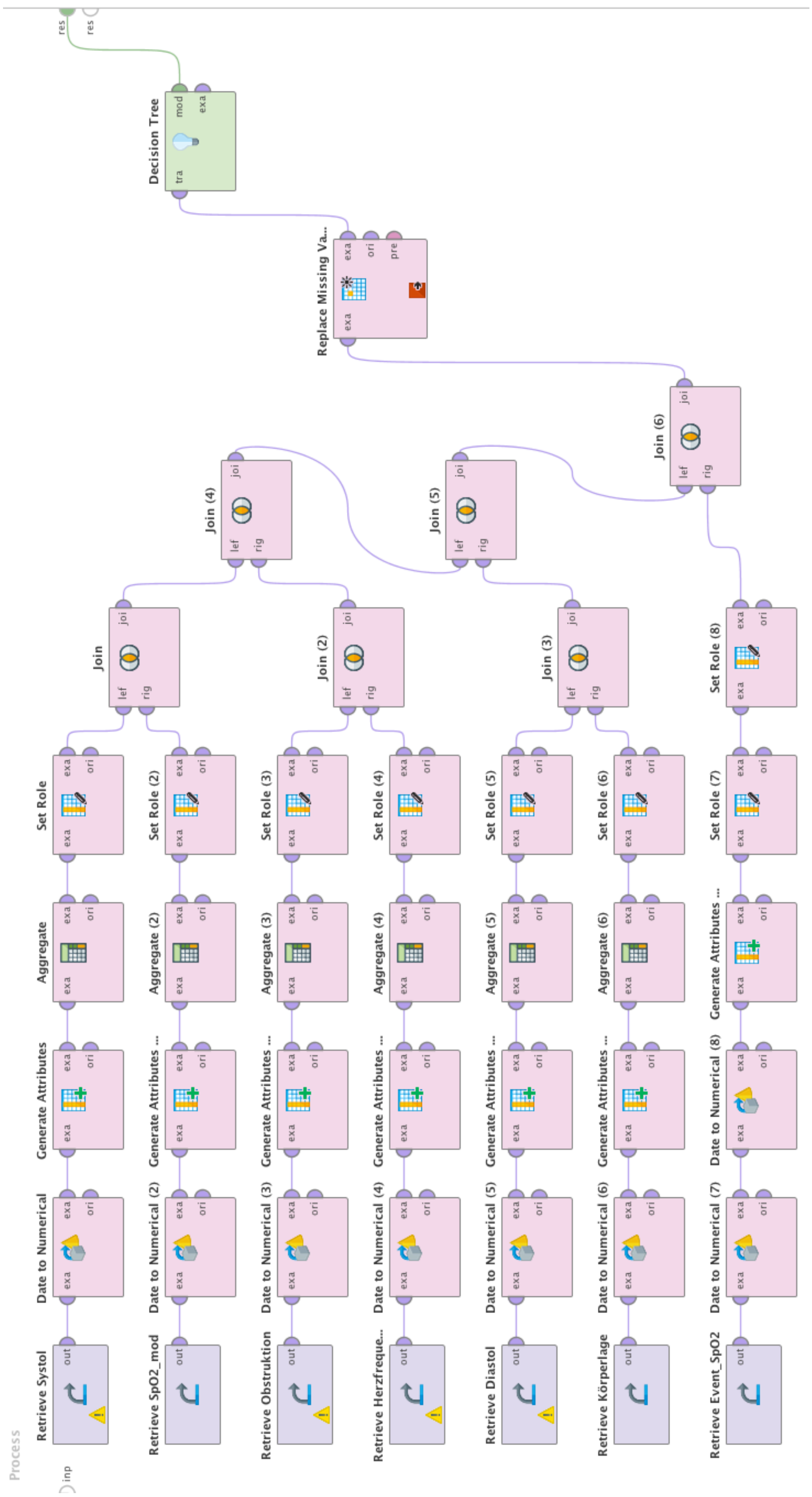


Figure 5.71: Process in Rapidminer for finding a rule for oxygen desaturation

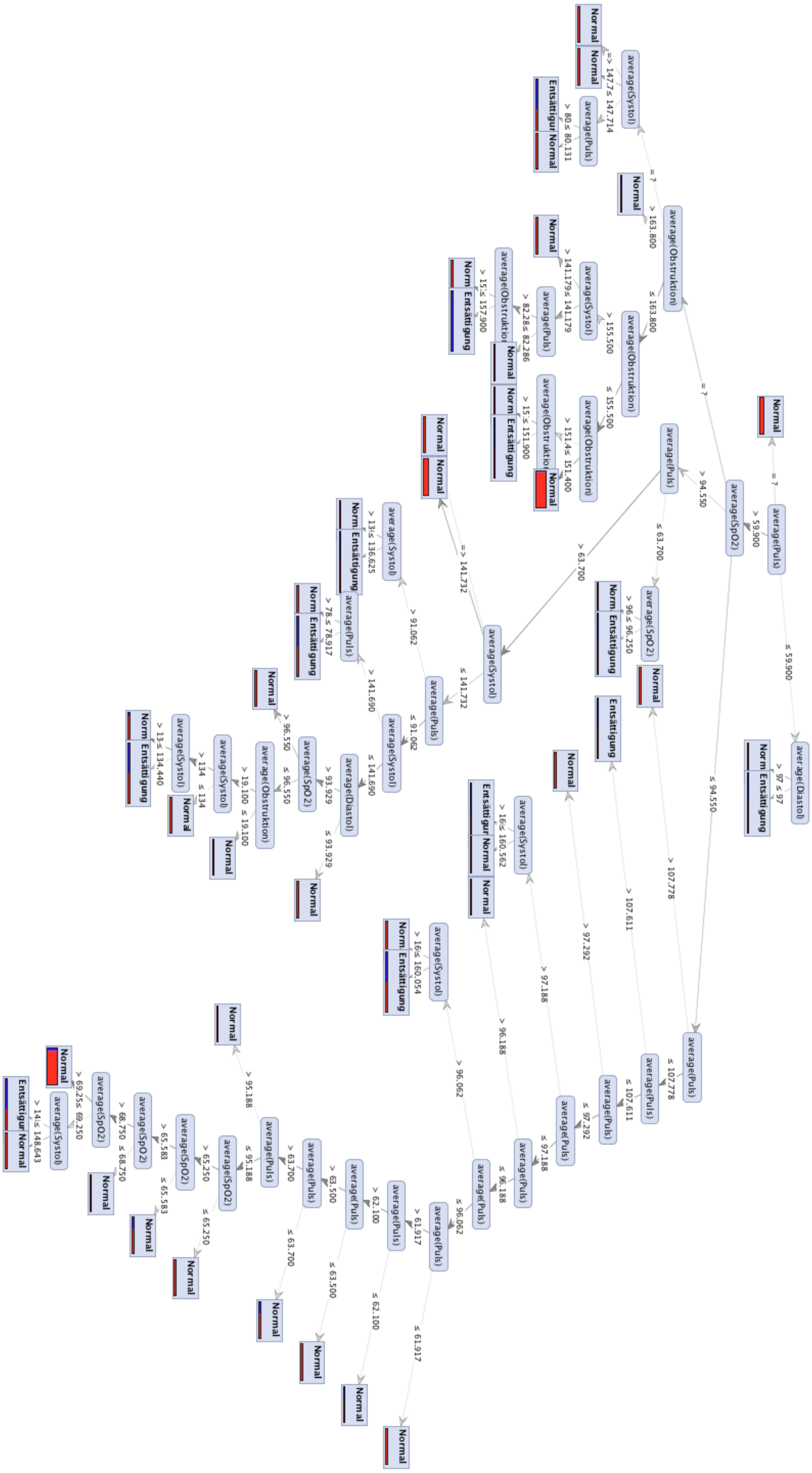


Figure 5.72: Decision tree for desaturation events

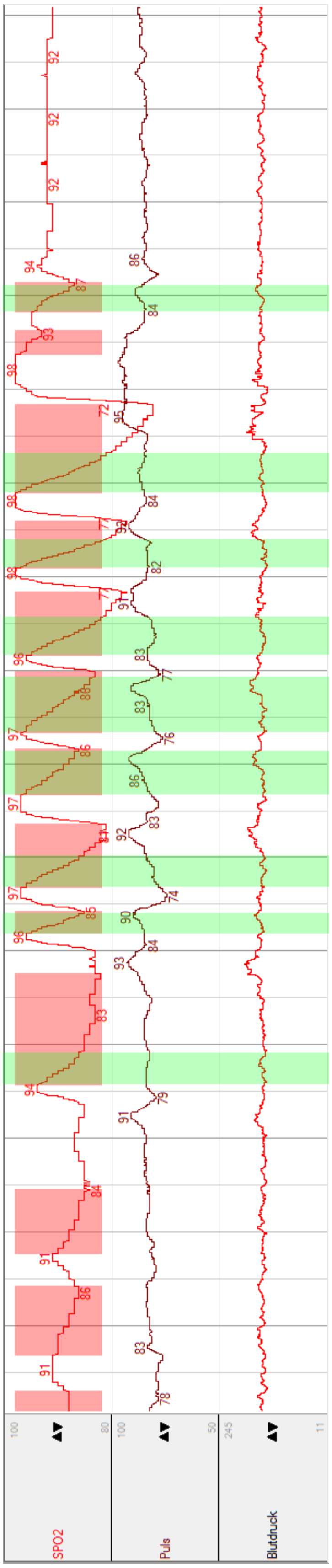


Figure 5.73: Comparison of desaturation events derived from the decision tree algorithm and manually marked ones

values are generated, in this case the four severity levels of ARDS (none, mild, moderate and severe). Afterwards all the scoring parameters are removed from the dataset by selecting only the other attributes to be processed. After telling Rapidminer with the "Set Role" command which attribute should be the target classification the decision tree algorithm is executed.

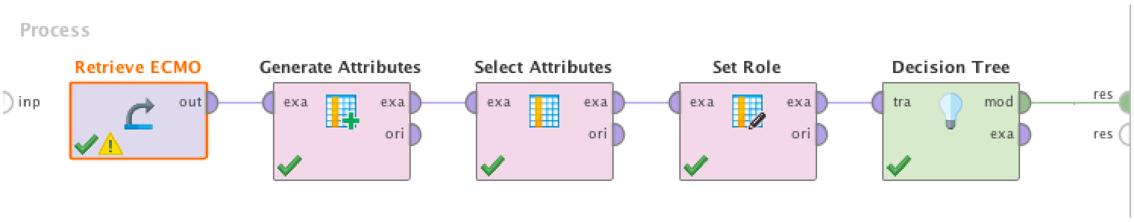


Figure 5.74: Process in Rapidminer for generating a decision tree upon the ARDS training data

5.6.4.3 Results

Figure 5.75 shows the resulting decision tree from processing the training data. The leftmost branch is an artifact from missing values in the training data. We can see that, as expected, the partial pressure of oxygen in the blood (pO2) is a crucial parameter for classification of ARDS. From the resulting tree we can derive that a pO2 value between 26.4 and 215 correlates in most cases to a moderate form of ARDS. When looking at the exact results (severe=55, none=9, mild=18, moderate=77) it is save to say that we found a rule that is good enough to be used for evaluating new incoming patient data and mark them as a possible case of ARDS if the rule matches.

The performance or accuracy of the learning process was given with 54.21% ± 1.87%. The detailed results of the accuracy measurement are shown in table 5.2.

Figure 5.76 shows how the rule would be translated into the TARDIS framework. We would now present the rule to the expert for validation. Afterwards it can be added to the rule base and executed whenever data of new patients arrives.

5.6.4.4 Improvements

When knowledge should be extracted from data with data-mining techniques the amount of training data is always a crucial factor. Usually the number of training data sets corresponds directly with the quality of the results. To get acceptable results from smaller amounts of data a technique called “k-fold cross validation” is used. The training data is divided into k chunks. Then the learning process is performed k times while every time a different chunk is used for validation while the other $k-1$ chunks are used for training. The data-set seems to be k-times larger and the results are improving. We added a k-fold cross validation node into the Rapidminer process, replacing the decision tree node. The inside of the validation node is depicted in figure 5.77. We have chosen the default value of $k = 10$.

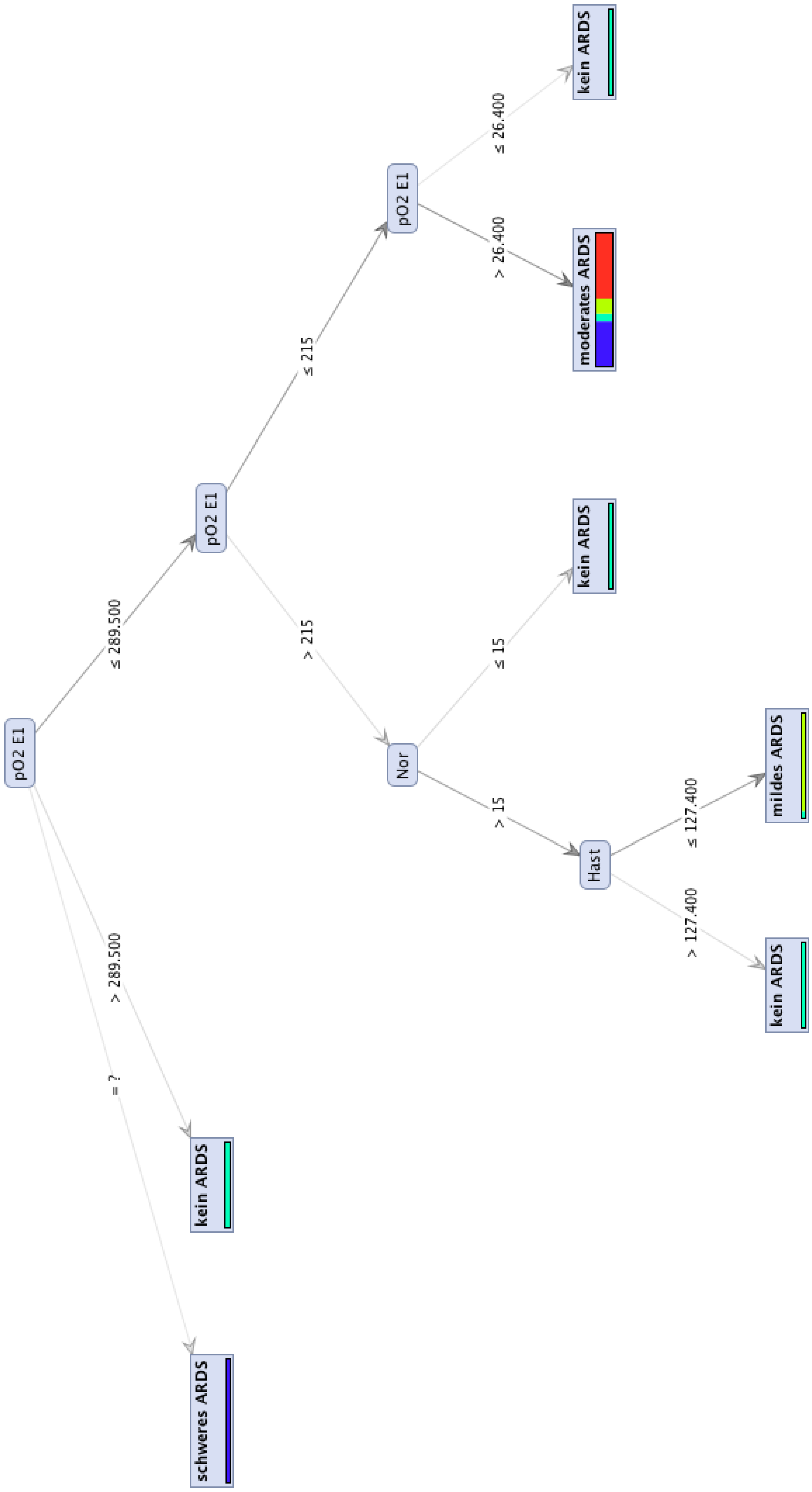


Figure 5.75: Generated decision tree for classification of ARDS severity

Table 5.2: Accuracy of the learning process

	true "severe ARDS"	**true "no ARDS"**	**true "mild ARDS"**	**true "moderate ARDS"**	**class pred.**
pred. "severe ARDS"	15	1	1	11	53.57%
pred. "no ARDS"	3	32	10	2	68.09%
pred. "mild ARDS"	3	6	6	1	37.50%
pred. "moderate ARDS"	38	9	13	63	51.22%
class recall	25.42%	66.67%	20.00%	81.82%	

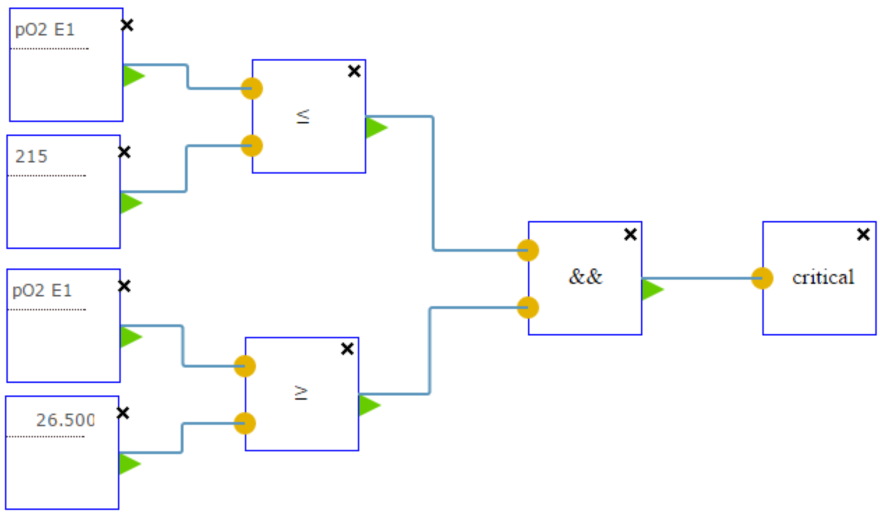


Figure 5.76: Rule derived from decision tree

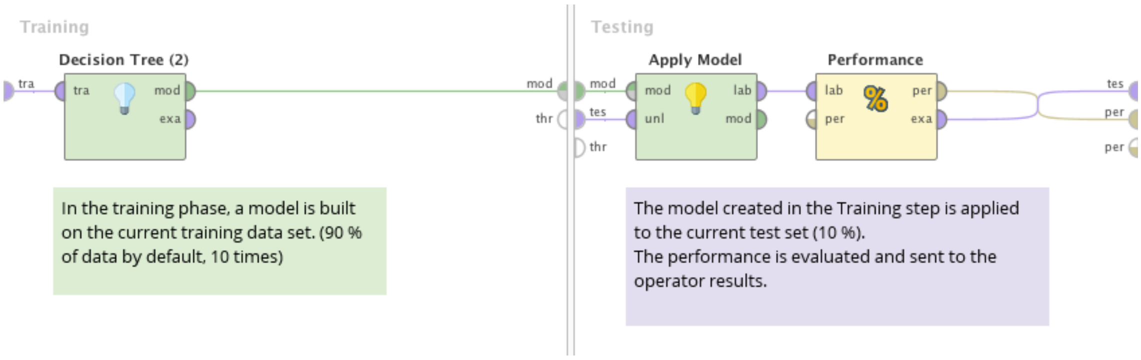


Figure 5.77: K-fold cross validation in Rapidminer

The cross validation node also provides an accuracy value for the learning process. Table 5.3 shows the single values while the global accuracy was 56.99% ± 9.93%.

Table 5.3: Accuracy of the learning process with k-fold cross validation

	true "severe ARDS"	**true "no ARDS"**	**true "mild ARDS"**	**true "moderate ARDS"**	**class prediction**
pred. "severe ARDS"	4	0	0	0	100.00%
pred. "no ARDS"	0	32	3	0	91.43%
pred. "mild ARDS"	1	4	9	0	64.29%
pred. "moderate ARDS"	54	12	18	77	47.83%
class recall	6.78%	66.67%	30.00%	100.00%	

Rapidminer provides the possibility to calculate optimized parameters for the decision tree algorithm. Since this is taking a lot of time to calculate, it is not suitable to calculate these optimized parameters for every rule-set. It took about 35 minutes on an average PC to calculate the parameters seen in table 5.4. After the calculation we used these values and performed another run of the decision tree algorithm. The resulting tree was much more complex as it can be seen in figure 5.78. When looking at the overall accuracy, that was 67.40% ± 11.15% with the optimized parameters, the new process seems to perform much better. The detailed accuracy values in table 5.5 show that for our use case the previous results were more appropriate. The higher prediction rate for the "no ARDS" classification is more useful in the clinical setting as the doctors want to minimize false positives.

The wider tree and therefore much more complex resulting rule is also worse for presenting it to the expert who will struggle to understand the meaning of the rule.

Table 5.4: Parameters for the decision tree algorithm before and after optimization

parameter	**pre optimization**	**post optimization**
criterion	gain_ratio	gain_ratio
maximal depth	20	19
confidence	0.25	0.25
minimal gain	0.1	NaN
minimal leaf size	2	1
minimal size for split	4	60
number of prepruning alternatives	3	3
overall accuracy	56.99% ± 9.93%	67.40% ± 11.15%

Table 5.5: Accuracy of the learning process with parameters suggested by the optimization

	true "severe ARDS"	**true "no ARDS"**	**true "mild ARDS"**	**true "moderate ARDS"**	**class prediction**
pred. "severe ARDS"	45	1	5	20	63.38%
pred. "no ARDS"	1	33	0	4	86.84%
pred. "mild ARDS"	4	6	14	1	56.00%
pred. "moderate ARDS"	9	8	11	52	65.00%
class recall	76.27%	68.75%	46.67%	67.53%	

5.7 Summary

We added a rule-based decision system to our telemedical system that is capable of analyzing the incoming data and react accordingly (see figure 5.79). We implemented a graphical editor to define the rules, that should be processed on the data, to enable also non-technical users to adjust the analysis to their needs. The decision system processes all incoming data from any defined data source and is able to filter and sort data and raise appropriate alarms and messages. A lot of different

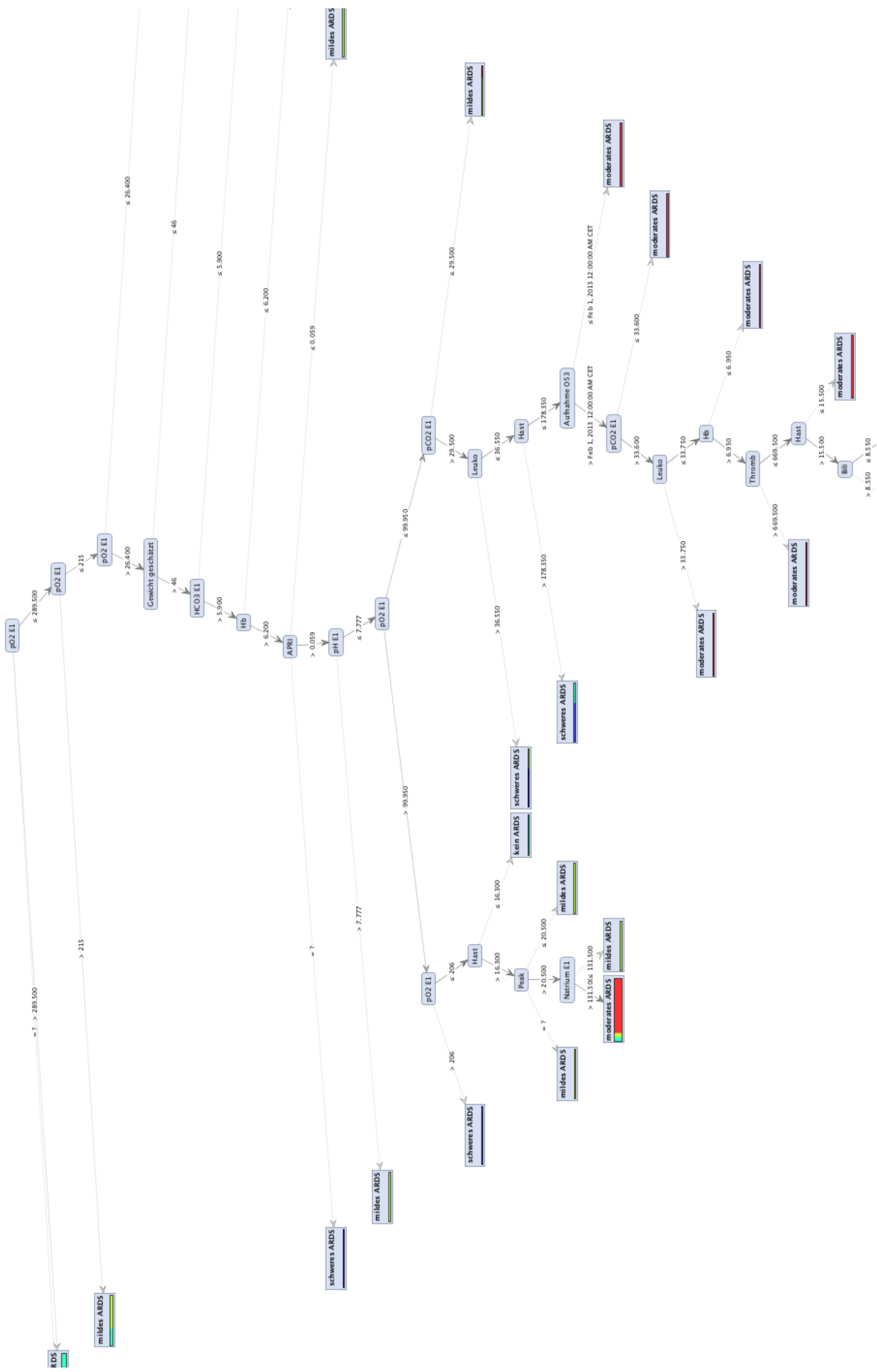


Figure 5.78: Generated decision tree for classification of ARDS severity after optimization of parameters

visualizations can be created from the rules. This allows the user to choose the visual representation of the data that fits the purpose of analysis best. Defined rules can even be transferred to the patients device for preprocessing the data before even sending it to the backend service. This allows to give a feedback to the patient without the need of a permanent connection to the backend or implement other kind of autonomy functions for the patients device. A rule generator analyzes the incoming data and their evaluation by the user to learn and extract possible new rules. These new rules are presented to the user and can be added to the rule base when they seem to be helpful. This chapter described the implementation and evaluation of

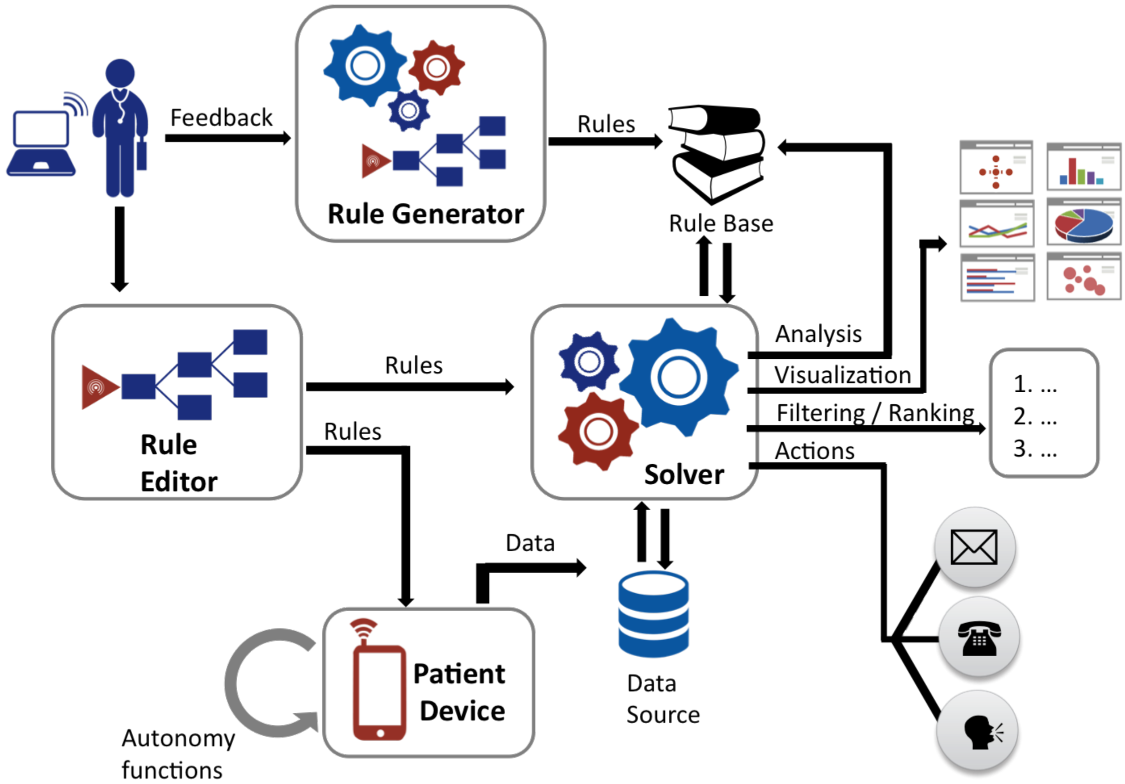


Figure 5.79: Rule-based system for analysis of patient data TARDIS

a rule based decision system that was integrated into our telemedical system. We showed that the creation of rules for automatic analysis of the incoming data can even be done by the medical personnel. This enables the experts to transfer part of their specialized knowledge into the system to perform pre-analysis of the data and application of filters or sorting the data in beforehand to reduce the workload of the medical personnel working with the telemedical system. We were also able to transfer the decision system to other fields of application without altering it which is possible due to the independence from the type of data that is processed. The use in an industrial setting, by analyzing the data of an industrial robot, helped to identify interesting features that could be added to the system to improve it even further. Furthermore we were able to analyze the incoming data in order to automatically generate rule-sets that can help the users to improve the rule base. This enables the system to improve itself and it's performance by creating new rule-sets that can be verified by the experts and then be used for automatic data analysis.

Chapter 6

Conclusions

6.1 Summary

6.1.1 A generic telemedical system

Due to the demographical trends the health care systems and medical care in future sociality are confronted with a lot of problems. The use of telemedical systems can support the treatment of different diseases and solve these issues. Tele-medicine systems can support the treatment of specific diseases at economic costs, being of particular interest in the future demographic trends. During the development and implementation process of the system the special requirements for COPD, dialysis and intensive care have been considered. These diseases play an important role in the healthcare systems of the world and imply many different requirements for the system. Based on the different requirements of these scenarios, the proposed system offers a high flexibility and new diseases can now be integrated easily. This offers the opportunity to use the advantages of telemedicine for many diseases with minimal amount of implementation work. Furthermore, it saves a lot of costs to use a generic infrastructure for different diseases instead of many small specific solutions.

Figure 6.1 shows an overview of the telemedical framework. On the patients side, the different sensors are connected to a COTS smartphone that collects the data and is responsible for the preprocessing and transmission of the data. It is also used for interaction with the patient, like answering questionnaires, to realize communication with the supervising medical personnel and provide feedback. The medical personnel can connect to the system with any standard hardware by using a browser. Such the telemedical center does not need to reside in a special building. They can view all the crucial data of the patients, perform analysis on the data or use their devices for communication with the patient or other medical personnel. The backend provides all the needed functionality for storage and analysis of the data. It handles communication links if no direct communication is possible and provides interfaces for all users of the system, including external users like other clinics, researchers or relatives.

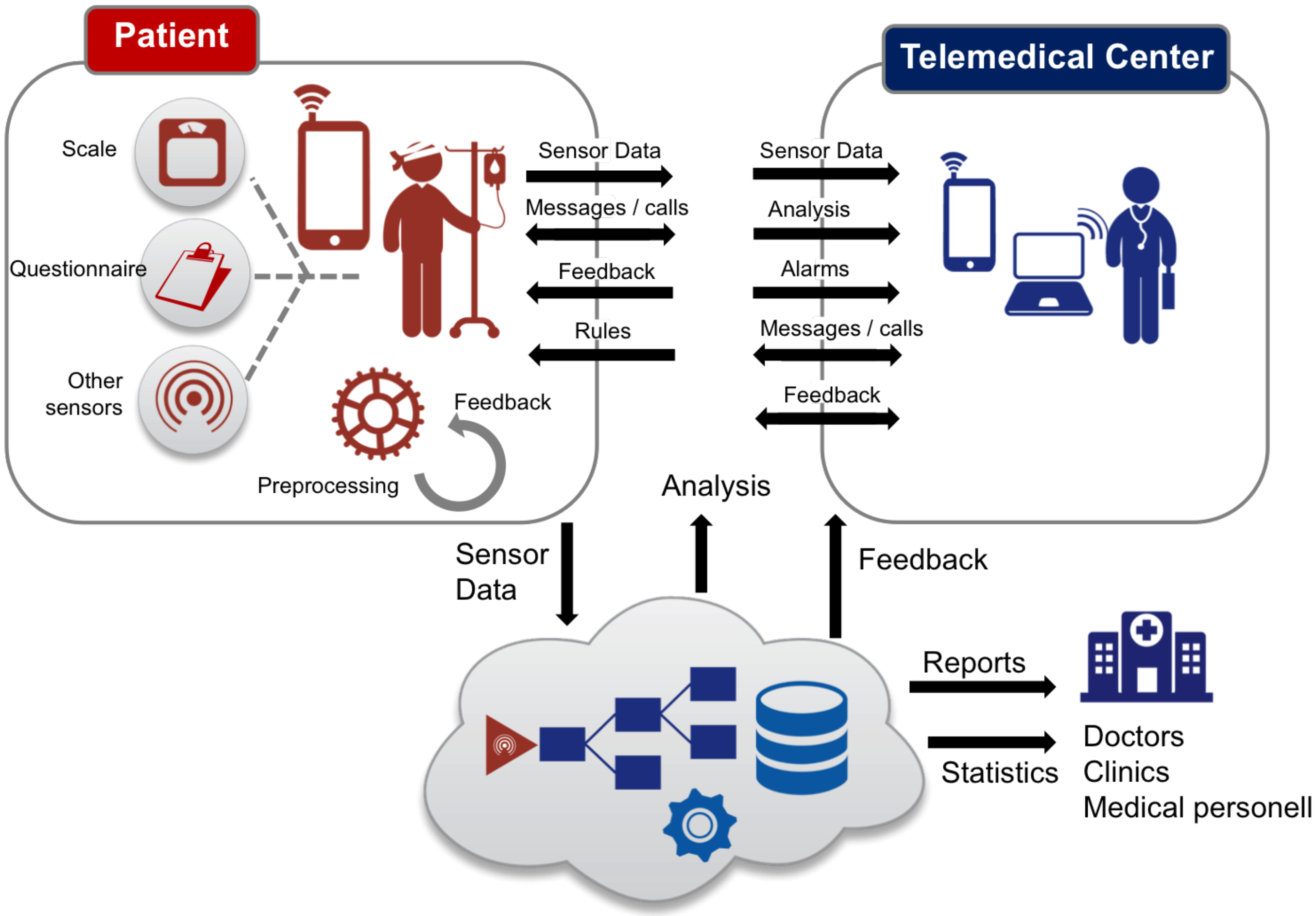


Figure 6.1: Communication links between patient and doctor

6.1.2 Fast and easy data transfer and communication

Figure 6.2 summarizes the use of the telemedical system in the scenario of intensive care. Smaller hospitals (left side) are able to use standard hardware to send data and images to the backend (top). Since the whole system is built upon standard web-based technologies no initial configuration or installation is needed. That allows even new clients to use the system without initial contact to the experts and pave the way for a broad use of the system. The specialists (right side) have instant access to the data and can perform a direct video and audio communication with the medical personnel at the smaller hospitals to decide if and how the patient has to be transferred to the specialists for a more specialized treatment.

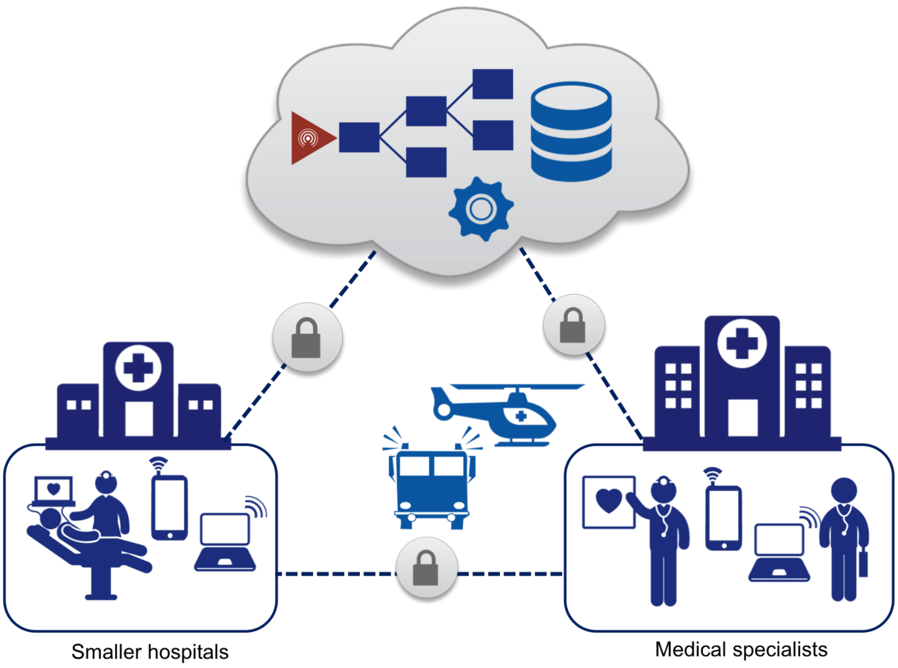


Figure 6.2: Communication between physicians

6.1.3 Rule based analysis

We integrated a very flexible rule-based decision framework that is capable of covering all the tasks for autonomous functions and data analysis in our telemedical system. The different modules and capabilities can be seen in figure 6.3. Via the graphical rule editor even non-technical personnel is able to create rules for the analysis of the data. Based on the output of the rule solver, many different visualizations or actions can be performed. Many actions, like alarming or creation of messages, are already implemented, but the framework is easily extensible for further methods and actions. In the mobile devices at the patient the framework is used to manage an intelligent data transmission and does a brief preprocessing of the incoming data. On the remote workstation it is used for filtering and analyzing the data. The framework is Turing complete, which enables us to reuse it in other fields of applications, like swarm robotics or expert systems for industrial maintenance.

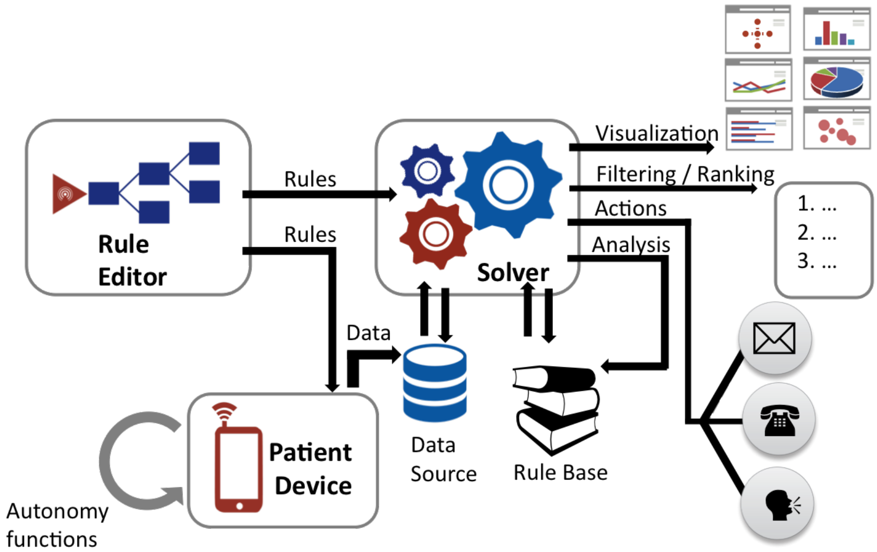


Figure 6.3: Rule based decision framework - Telemedical Applications with Rule based Decision- and Information-Systems (TARDIS)

6.1.4 Learning new rules

Additionally we added a machine learning process into the rule based decision system. This allows us to analyze the incoming data in order to generate new rules that can be presented to the users. If the user wants to keep the rule, he can add it to the existing rule set. Figure 6.4 summarizes the process of rule generation with the added rule generator. Its purpose is to help the user improve the system by extending the rule base. Data mining on the patient data holds the opportunity to create new knowledge of the progress of diseases or correlations between parameters. By adding more rules to the rule base the analysis gets better and the medical personnel gets more support at monitoring the treatment and the patients health status.

6.1.5 Evaluation

The tests of the system and its different modules with users of the different domains resulted in a very positive feedback. The use of COTS hardware lead to a high acceptance of the system both on the patients and the clinical side. Due to simple and intuitive interfaces very little training was needed for the users to get used to

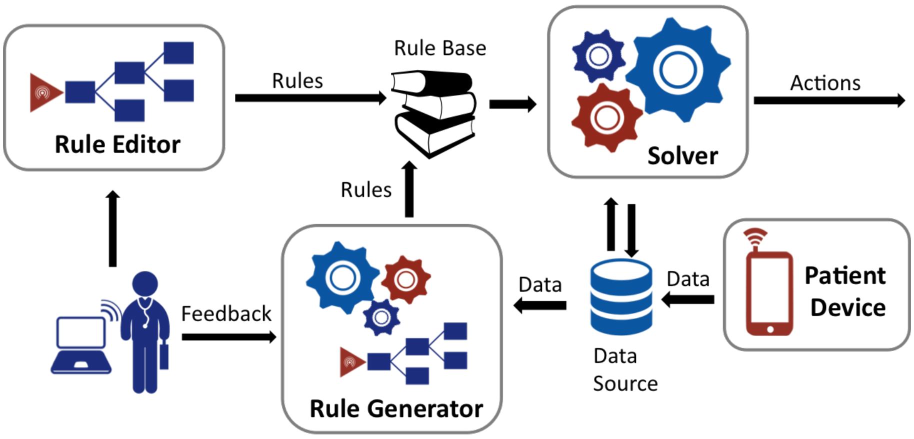


Figure 6.4: Process of creating rules for improving the rule base

work with the system. Patients reported a feeling of being well supervised while residing at home by the fact that physicians anytime had access to their recorded vital data. The generic design of the system allowed the application in the different fields of COPD, dialysis and intensive care (section 5.4.6). We also used the system to analyze data from an industrial production line (section 5.5). In these settings the data analysis can be used for optimization of the production process. Other applications, like the use in mobile robotics, are also possible.

6.1.6 User reactions

The system was developed in close cooperation with future users. Besides the permanent feedback, that flowed into the development, we got some reaction to the nearly completed system. The medical personnel from "Heimbeatmungsservice Brambring Jaschke Bad Kissingen", who care for home mechanical ventilation patients commented on the telemedical infrastructure:

> "The technical innovation lies on the part of the novelly interactivity of the treatment. An adaptive approach is possible through iterations of changes and observation. This leads to a earlier, situation-adequate reaction in contrast to traditional visits to the doctor in fixed, larger intervals, independent of the current health status. [...] Altogether a qualitative improved treatment benefits from these innovative approaches, while simultaneously costly complications can be avoided by early intervention." [144]

Doctors and nursing staff from "Missionsärztliche Klinik Würzburg", who worked with the telemedicine infrastructure in the area of tele-monitoring of COPD patients reacted to the results as follows:

> "The project brings, compared to the present situation, notable improvements in the areas of prevention (by identifying lead indicators),

diagnosis (continuous monitoring provides more data than traditional visits to the doctor) and therapy (enhanced efficiency of health care by new, adaptive possibilities for therapy and interaction mechanisms)." [144]

6.1.7 Research questions

In this work some questions were raised, that are logically grouped and whose answers are summarized in the following section:

Who are the main actors in a complete telemedical system and what are their needs?
During the requirement analysis for the telemedical system we identified the major stakeholders in a telemedical system (see section 4.3.1). First of all the patient and its supervising medical personnel who want to maximize the efficiency of the treatment while reducing the effort. Medical personnel needs to exchange medical expertise among each other. Other medical personnel, like the family doctor or nursing services, need to keep updated about the treatment process. Even an information of relatives is possible. Finally the communication with health care providers is necessary for efficiency and cost reduction. In our telemedicine system we provided interfaces to allow a connection to all these stakeholders.

How can the spatial distance between patient and supervising medical personnel be bridged efficiently? What is necessary to bring the expert knowledge to the place where it is needed? How can medical expertise adequately be transfered over distances? Which components does a generic telemedicine infrastructure require?
Our three main modules, the patient device, backend and telemedical workplace, interconnect the complete system and offer everything needed for connecting patients and doctors or medical personnel among each other (see chapter 4). The tests showed, that our system is capable to connect patients and medical personnel in an efficient way. This is reflected in the easy usage of the system, that was complimented by different user groups, and the manifold possibilities the system offers for knowledge transfer and communication. These include sensor data and image transfer, messaging and live video communication.

What are the requirements for medical systems to be easily integrated in a telemedical system? Which COTS products can be used for telehealth?
On the patients side we already integrated some commercial medical sensors (see section 4.3.3). We chose Bluetooth sensors for our use cases as they can be easily connected to a standard smartphone, but this is no limitation. A wide variety of sensors can be integrated, as long as they provide an interface to get the sensor data. Sometimes adapters in hardware or software might be necessary. The use of a COTS smartphone as a patient device was a good choice as they provide a lot

of functionality out of the box and they are already widely in personal use. That simplifies the access to the system for many patients.

Which network and link characteristics are suitable for telehealth applications?
The tests on different networks and links showed that for standard telehealth applications nearly every connection is suitable (see section 4.9). We implemented some methods to adapt the data transfer to the current link conditions. Some technologies already include techniques, like graceful degradation, that react to worsening link qualities. Since the critical parts of our use cases were completely built on asynchronous communication, the network infrastructure was less important. For live communication or live data transfer the link quality was normally good enough. When the system should be used for control scenarios, like adapting parameters of a medical device during use, the mechanisms for assuring link quality have to be revised.

What can be done to lower the technical and financial gaps for the broad use of telemedicine? How can the technical prerequisites be lowered or simplified?
By using COTS smartphones, medical sensors and infrastructure we built a system that is affordable even for smaller hospitals or practitioners (see chapter 4). The usage of browser based interfaces or smartphone applications is known to most of the patients and medical personnel such that expensive training is not necessary.

How can different diseases be treated with the same telemedical infrastructure? Can a telemedical system be completely abstracted from any characteristics of specific diseases?
We showed that our system could be used in three different medical scenarios (monitoring of COPD patients at their homes, support of home dialysis and connecting medical experts in the area of intensive care, see section 4.2). Furthermore, the system was used in a completely different field of application to analyze data of an industrial robot (see section 5.5). This abstraction from any disease was possible by consequently generalizing modules and abstracting from contents of data streams. The complete design of the whole system is build to support any kind of data while minimizing the need of adoptions. This makes the system unique in its field.

How can we reach a high scalability of telemedical systems? Can the decreasing doctor-to-patient ratio be compensated by the use of telemedicine? How can the workload be reduced for the medical personnel that take care of the patients?
With the rule-based analysis of data and many possibilities for medical personnel and patients to configure the system we created the potential to be highly scalable (see chapter 5). The workload of medical personnel could be reduced by adding analysis, filters and sorting functions. It is yet to be seen if the effects are big

enough, by performing a test with a larger amount of patients. The tests showed that the system performs very well, even with high amounts of users.

Does a telemedical system helps creating new knowledge about the progress of diseases? How has the infrastructure to be designed in order to prepare higher level analysis of the data? Can the use of telemedical systems increase the prevention of diseases?
Data mining offers the potential to gain new knowledge about the data and its correlations. We added data mining functionality to create and suggest rules for the rule-based system (see section 5.6). This can be used to try and extract knowledge about correlations in the data or the progress of diseases. For the first time the medical personnel has one system, that continuously collects data from patients and allows to perform data mining analysis on up-to-date data. Despite we have not integrated algorithms or functions to gain new medical knowledge, we provide the structure to perform such analysis. The infrastructure is prepared by providing access to the data, in anonymized form, to perform analysis on the data of all patients in the system. Such analysis go far beyond the scope of this work, but are very promising to gain new medical knowledge and maybe find indicators for prevention of some diseases.

How should such a system be designed to be efficiently used by non-technical users? Can the system give feedback to patients about the progress of the treatment? What are possible features that increase the safety of patients or the medical personnel?
By frequently obtaining feedback from users of the system, the use of standard components whenever possible and a strictly user centered design we created a system that is easy to use, even for non-technical users. The necessity for training is minimal. Messaging and live communication allows the doctor to communicate and give feedback to the patient. With the rule-based system, the doctor can create rules and transmit them to the patients device (see chapter 5). This creates a semi-automatic feedback system, that runs autonomously on the patients device. These customized rules can also be used to implement safety functions for both patient and medical personnel. Additionally, system-side functionality assures the security of data transfers and data storage for privacy protection.

6.2 Innovation overview

This works main research focus lies on addressing the problems of scalability and knowledge transfer in telemedical systems. The result is a generic telemedical infrastructure that is not constrained by specific characteristics of diseases or sensors and their parameters. The combination with a highly flexible rule based framework for analysis of different kind of data offers a high scalability of the system at growing amounts of patient and data. The generic design allows the usage of the system in other disciplines too, like industrial robotics or other systems that needs autonomous decisions.

Figure 6.5 summarizes the innovations that have been developed during this work. On the clients side we use COTS medical sensors and smartphones to realize the patients interface for the system. It also includes autonomy functions, by using the rule-based framework, and sensor fusion. It was evaluated for three different diseases to prove its generic structure. The data is collected automatically and transfered to the backend asynchronous or live, depending on the defined settings and the current network characteristics. The medical personnel can access the data via the “digital patient chart”, an intuitive interface that combines all the functionality of the system. It provides a live video module to communicate with the patient or to consult medical experts when needed. It is built platform independent, so no special hardware is needed to access the system. This allows a fast, easy and cheap access and operation of the system. Integrated in the backend are data analysis functions for creating visualizations of the data, which were evaluated for data of the medical and industrial application domain. The rule-based decision framework executes user created rules on the data for providing automatic notifiers, visualization or other actions, based on the current data. The decision framework was also evaluated with data from both the medical and the industrial application domain. An automatic generation of hypothesis on incoming data was integrated as an extension for the decision framework. It creates suggestions for new rules, that are presented to the user to decide if the rule should be added to the rule base. This learning module was evaluated with data from the medical domain. In detail the work that has been done provides the following aspects:

- Creation of a complete telemedicine infrastructure that is independent of disease or sensor types (Chapter 4)
- Definition and measurement of requirements for different communication links used for telemedicine (Section 4.9)
- Development of a rule based decision system (Section 5.2)
- Integration of the rule based decision system into the telemedicine infrastructure (Section 5.3)
- Evaluation of the decision system with use cases of the (tele-) medical domain (Section 5.4)
- Evaluation and extension of the decision system with use cases of the industrial domain (Section 5.5)
- Adding automatic generation of hypotheses on incoming data to form new rules (Section 5.6)

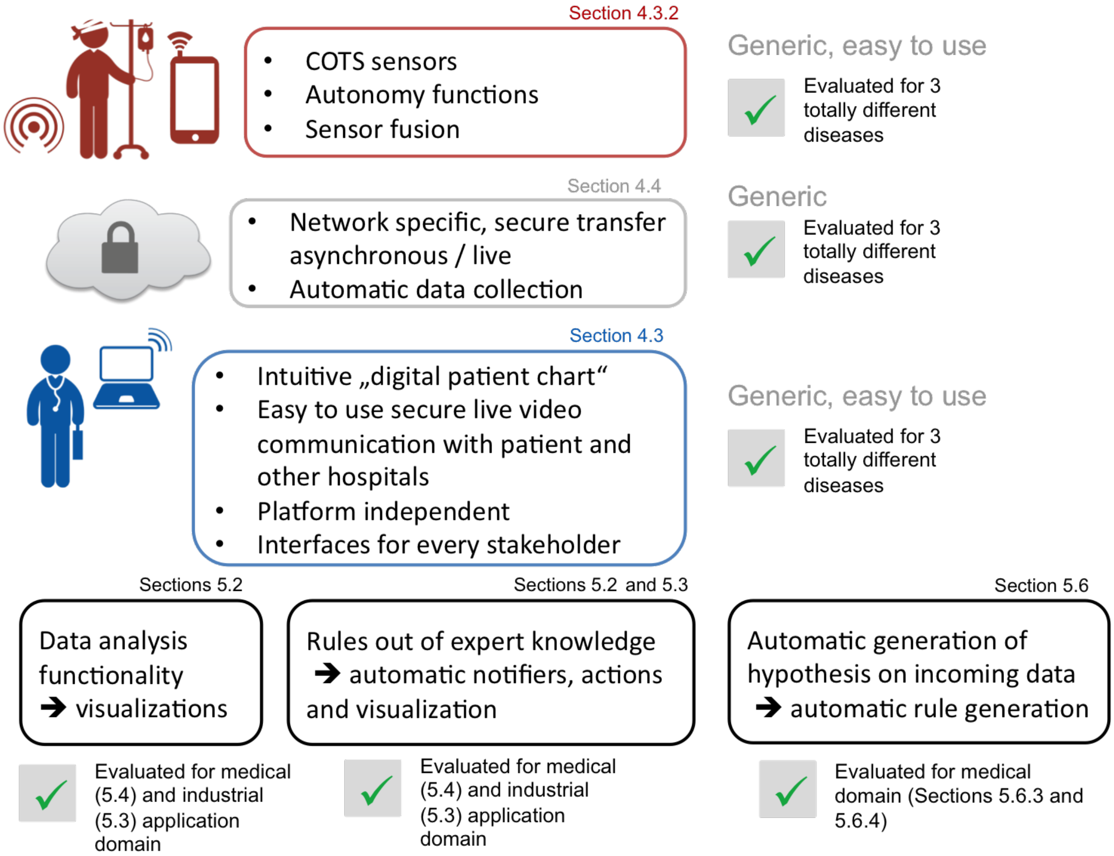


Figure 6.5: Summary of the innovations

With our system a new, innovative workflow for supervising patients is now possible for the first time. Figure 6.6 summarizes the workflow. After specifying the characteristics for the patients disease, the physician can select appropriate sensors and equip the patient. Corresponding rules can be defined for the monitoring of the patient and creation of autonomy functions and proper alarming or visualizations. The system takes care of the automatic data collection from the sensors and the optimal data transfer strategies while securing the transfer. During the supervision and treatment of the patient, the medical personnel has access to all the data of the patient. Live video communication between the medical personnel and the patient or medical experts is possible and allows fast responses to critical events or consultation of experts for a specific domain, to optimize the treatment. The automatic hypothesis generation creates new rules for analyzing the data and helps the physician to improve the system.

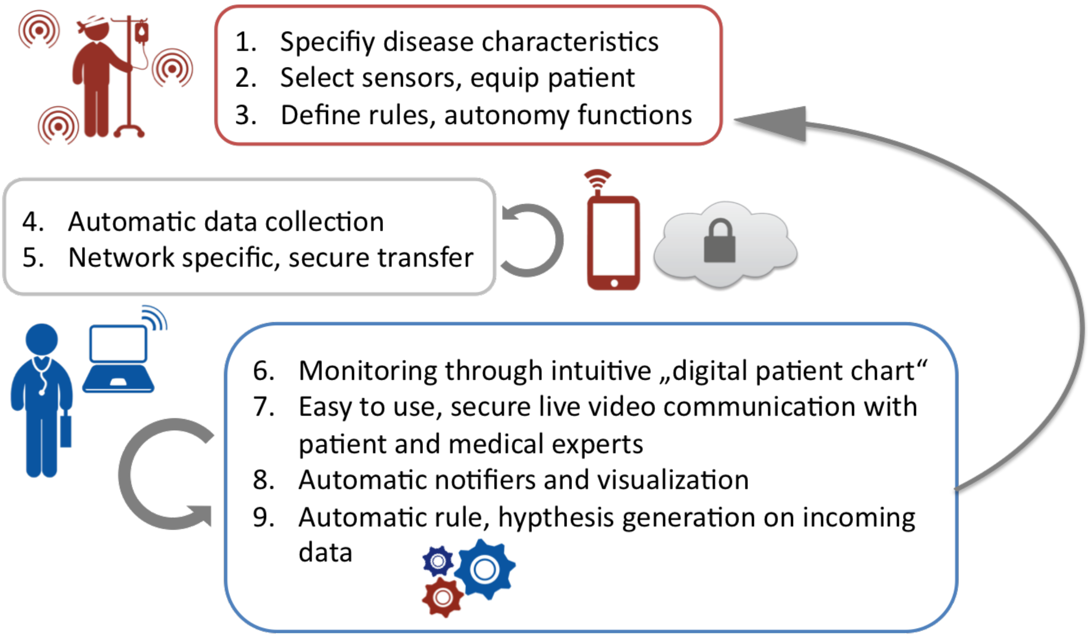


Figure 6.6: Innovative workflow in an intelligent telemedicine system

6.3 Suggestions for future work and further applications

The presented system offers a highly flexible and mobile telemedical support for patients. This provides a new quality for the treatment of patients at home and improves their quality of life while allowing reduction of costs. Therefore the presented system shows a way to deal with the demographic challenges of our modern societies. The proposed system was implemented and tested successfully with patients. The achieved results were very promising. Due to the usage of COTS hardware and a straight focus on usability, the system was highly accepted on both sides, doctors and patients. Patients reported a feeling of being well supervised even if there was no regular contact to the supervising doctors. Also, a higher self awareness of the treatment effects on the diseases progression was recognized by the patients. Due to continuous measurements at home and the possibility to interact with the patient while seeing the live sensor data, the physicians could keep closer contact with the patient and it was easier to evaluate the patients status.

The system has yet to be tested with a larger number of patients, physicians and nurses to prove its scalability in higher scales and give detailed results of the performance of individual modules. Performing a large scale test run would provide detailed insights on the amount of cost reduction, enhancement of the treatment and workload reduction. These results are needed to discuss accounting modalities with health care providers, as these rarely exist for any kind of telemedicine treatment.

Implementing connectors for additional medical sensors increases the number of possible supervised diseases. A broader user base would then lead to more data that can be analyzed and correlated in order to find new medical knowledge or learn from other disciplines. For a usage of the telemedicine system in the regular treatment processes, it has to be checked if medical device regulations of the respective countries apply and changes to the system are necessary. Privacy issues have to be solved, for researchers to be able to access the large amount of patient data, as it holds the potential to perform studies and generate new insight and knowledge about the progress of diseases. Generating anonymized data for research purposes could be a way to be compliant with privacy restrictions.

The extension of the analysis framework with new algorithms would provide more possibilities to gain knowledge about the diseases and their treatments. To make the framework even more powerful we plan to add user definable macro blocks that can be used to aggregate often used rule combinations into one single block. This increases the clarity of the rules and allows a faster working with the graphical editor. The existing interfaces allow the integration of other algorithms or frameworks for analyzing the data. Further research at optimization of the parameters or algorithms for the learning functionality could improve the quality of the resulting suggested rules. The needed feedback for the learning algorithms could be generated from the usage behavior of the medical experts to avoid the additional work of explicitly tagging patients data. By analyzing the way experts look at the data of the patients this feedback could be extracted or even used to generate new rules for future analysis of the data.

List of Own Publications

[1] Matthias Görs, Markus Schäfer, Michael Albert, Roland Marx, and Klaus Schilling. **Link analysis for networked control systems over mobile and wireless communication networks in telehealth**. In *Proceedings of the 1st IFAC Conference on Embedded Systems, Computational Intelligence and Telematics in Control (CESCIT)*, pages 1–6, Würzburg (Germany), April 2012.

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Appendix A

Selection of sensors for monitoring COPD patients

Sensor	messbare Parameter																							
	SaO2	Puls	Aktivität	Gewicht	FEV1	Vitalkapazität	Peakflow	Subjektives Befinden	Atemnot	Beurteilung Sputum	pCO2	Atemfrequenz	P_max	V_t(i/e)	f	AMV	I/E	P_cuff		Dokumentationen (Wund, Handzeichen, ...)		Fragebogen integrierbar		Therapie-Compliance
Pulsoximeter	x	x																						x
Aktimeter			x																					x
Waage				x																				x
Spirometer					x	x	x	x	x	x												x		x
Kapnometer											x													x
Beatmungsgerät												x	x	x	x	x	x							x
Cuffdruck Messgerät																		x						
Handy			x																			x		x

	Abtastrate (Übertagungshäufigkeit)																							
COPD	mögl. Durchgehend (1 x täglich)	mögl. Durchgehend (1 x täglich)	mögl. Durchgehend (1 x täglich)	1 x pro Tag (1 x täglich)	1 x pro Tag (1 x täglich)	"	"	"	"	"	1 x pro Tag (1 x täglich)										1 x pro Tag (1 x täglich)		mögl. Durchgehend (1 x täglich)
Heimbeatmung	mögl. Durchgehend (mehrmals täglich)	mögl. Durchgehend (mehrmals täglich)	mögl. Durchgehend (mehrmals täglich)									mögl. Durchgehend (mehrmals täglich)	mögl. Durchgehend (mehrmals täglich)	mögl. Durchgehend (mehrmals täglich)	mögl. Durchgehend (mehrmals täglich)	mögl. Durchgehend (mehrmals täglich)	mögl. Durchgehend (mehrmals täglich)	mehrmals täglich (nach jeder Messung)		mehrmals täglich (nach jeder Messung)		1 x pro Tag (1 x täglich)		mögl. Durchgehend (1 x täglich)

Werte:	mögl. Durchgehend (1 x täglich)
	1 x pro Tag (1 x täglich) <> Prio 3
	mehrmals täglich (nach jeder Messung) <> Prio 2
	mögl. Durchgehend (mehrmals täglich) <> Prio 1

Größe	Zumutbarkeit	Auswertelogik	Bedienung	Kommunikation	Energieversorgung	Kosten
-klein -mittel -groß	- nicht - bedingt - voll		- einfach - mittel - schwer		- Batterie - Kabelgebunden	- günstig - bezahlbar - teuer
klein: verschiedene Bauarten Vorhanden (Fingerclip, Pflaster, …)	bedingt: nächtlich bzw. einem kurzen Zeit Intervall pro Tag		einfach: einschalten, anstecken	verschiedene: Bluetooth, …	Batterie: relative lange Lebensdauer	bezahlbar
klein: in einigen Geräten (z.b. Handy) integriert. Verschiedene Bauarten (Anstecker, Brustgurt, …)	bedingt: Aktimeter sind in der Bauweise klein und könnten in den Tagesablauf integriert werden		mittel: aktivierung des Aktimeters könnte unter Umständen kompliziert sein.	verschiedene: Bluetooth, …	Batterie: relative lange Lebensdauer	bezahlbar
groß: Größe einer normalen Personenwaage	voll: einmal pro Tag sehr gut integrierbar		einfach: einschalten, wiegen	verschiedene: Bluetooth, …	Batterie: relative lange Lebensdauer	bezahlbar
mittel: Größe vergleichbar mit Zigarettenschachtel.	voll: einmal pro Tag sehr gut integrierbar		einfach-mittel: Konzepte vorhanden.	verschiedene: Bluetooth, …	Batterie: relative lange Lebensdauer	bezahlbar
Klein: vergleichbar mit Pulsoximeter	bedingt: nächtlich bzw. einem kurzen Zeit Intervall pro Tag		ka.	ka.	ka.	ka.
mittel-groß: aktuelle Beatmungsgeräte haben ca. die Größe eines Schuhcartons.	voll: je nach Patientengruppe muss das Beatmungsgerät verwendet werden. Nächtliche Unterstützung der Atmung, dauernd beatmet		mittel: Einweisung findet normalerweise statt.	verschiedene: Bluetooth, …	Kabelgebunden: Durch die notwendigkeit einer dauerenden und sicheren Stromversorgung	bezahlbar
klein-mittel: aktuelle Handy´s und Smartphone variieren in Größe und Gewicht. Größe bis ca. Zigarettenschachtel	voll: nahezu jeder besitzt sowieso ein Handy		einfach - schwer: je nach Typ und Anwendungen kann die Bedienung von einfach - schwer variieren.	verschiedene: Bluetooth, Wlan, UMTS, …	Batterie: je nach Bauart und Typ kann die Akkulaufzeit stark variieren. Mittelmäßige Laufzeit	bezahlbar

Appendix B

COPD Assessment Test (CAT) questionnaire

Ihr Name:

Heutiges Datum:

CAT
COPD Assessment Test

Wie geht es Ihnen mit Ihrer COPD? Füllen Sie den COPD Assessment Test™ (CAT) aus!

Dieser Fragebogen wird Ihnen und Ihrem Arzt helfen, die Auswirkungen der COPD (chronisch obstruktive Lungenerkrankung) auf Ihr Wohlbefinden und Ihr tägliches Leben festzustellen. Ihre Antworten und das Test-Ergebnis können von Ihnen und Ihrem Arzt dazu verwendet werden, die Behandlung Ihrer COPD zu verbessern, damit Sie bestmöglich davon profitieren.

Bitte geben Sie für jede der folgenden Aussagen an, was derzeit am besten auf Sie zutrifft. Kreuzen Sie (X) in jeder Zeile bitte nur eine Möglichkeit an.

Beispiel: Ich bin sehr glücklich 0 X 2 3 4 5 Ich bin sehr traurig

			PUNKTE
Ich huste nie	0 1 2 3 4 5	**Ich huste ständig**	
Ich bin überhaupt nicht verschleimt	0 1 2 3 4 5	**Ich bin völlig verschleimt**	
Ich spüre keinerlei Engegefühl in der Brust	0 1 2 3 4 5	**Ich spüre ein sehr starkes Engegefühl in der Brust**	
Wenn ich bergauf oder eine Treppe hinaufgehe, komme ich nicht außer Atem	0 1 2 3 4 5	**Wenn ich bergauf oder eine Treppe hinaufgehe, komme ich sehr außer Atem**	
Ich bin bei meinen häuslichen Aktivitäten nicht eingeschränkt	0 1 2 3 4 5	**Ich bin bei meinen häuslichen Aktivitäten sehr stark eingeschränkt**	
Ich habe keine Bedenken, trotz meiner Lungenerkrankung das Haus zu verlassen	0 1 2 3 4 5	**Ich habe wegen meiner Lungenerkrankung große Bedenken, das Haus zu verlassen**	
Ich schlafe tief und fest	0 1 2 3 4 5	**Wegen meiner Lungenerkrankung schlafe ich nicht tief und fest**	
Ich bin voller Energie	0 1 2 3 4 5	**Ich habe überhaupt keine Energie**	
		SUMME	

Appendix C

Selection of sensors for monitoring home dialysis patients

Sensor	messbare Parameter																						
	Artieriäller Druck	Venöser Druck	Transmembran Druck	Temperatur Dialysat	Temperatur Blut	Blutfluss	UF Rate	Puls	SaO2	Blutdruck	Gewicht (vorher und nachher)	Dauer	Fragebogen integrierbar		Kalium	Calcium	Bicarbonat	Blutzucker	Hämoglobin	Körperwasseranteil	Körperfettanteil	Körpermuskelanteil	
Dialyse Maschine	x	x	x	x	x	x	x			x		x	x						x				
Waage											x												
Smartphone													x										
Blutdruckmessgerät								x		x													
Pulsoximeter								x	x														
Bioimpendanzmessung																				x	x	x	
Blutzuckermessgerät																		x					
Blutgasanalyse															x	x	x	x					
Kommentar zu Abtastrate etc.	**Aktuell oder alle 5 Minuten sollten ausreichen Muss aktuell sein**							1/2 h		1/2 h	vorher/nachher				**Monatlich beim Arzt genügt**					*wird bei Uni alle 30 Minuten angefertigt*			interessant für Kinderdialyse

Größe	Zumutbarkeit	Auswertelogik	Bedienung	Kommunikation	Energieversorgung	Kosten	Häufigkeit /Wichtigkeit
-klein -mittel -groß			- einfach - mittel - schwer		- Batterie - Kabelgebunden	- günstig - bezahlbar - teuer	
groß: Dialyse Maschinen sind sehr groß	während der Dialyse		einfach - schwer: durch entsprechende Einweißung kann die Bedienung recht einfach werden. Stichwort: Usability	verschieden: aktuell gibt es einige möglichkeiten Daten der Dialysemaschine zu übertragen. Weiter Möglichkeiten können implementiert werden	Kabelgebunden:	bezahlbar	bei HD benötigt
groß: Größe einer normalen Personenwaage	während der Dialyse		einfach: einschalten, wiegen	verschiedene: Bluetooth, …	Batterie: relative lange Lebensdauer	bezahlbar	wird benötigt
klein-mittel: aktuelle Handy´s und Smartphone variieren in Größe und Gewicht. Größe bis ca. Zigarettenschachtel			einfach - schwer: je nach Typ und Anwendungen kann die Bedienung von einfach - schwer variieren.	verschiedene: Bluetooth, Wlan, UMTS, …	Batterie: je nach Bauart und Typ kann die Akkulaufzeit stark variieren. Mittelmäßige Laufzeit	bezahlbar	
klein-mittel: verschiedene Bauarten vorhanden.	während der Dialyse		einfach: anlegen, einschalten		Batterie: relativ lange Lebensdauer	bezahlbar	wird benötigt
klein: verschiedene Bauarten Vorhanden (Fingerclip, Pflaster, …)	während der Dialyse		einfach: einschalten, anstecken	verschiedene: Bluetooth, …	Batterie: relative lange Lebensdauer	bezahlbar	*in der Regel nicht Notwendig*
							nicht benötigt
							nicht beim Patienten benötigt

Appendix D

Questionnaire and interview for the requirement analysis for home dialysis

IS-06: Fragebogen – Med01

ZENTRUM FÜR TELEMATIK E.V.

Fragebogen:	**Bedarfsermittlung zu Telemedizin und Auswertungsunterstützung**
gerichtet an:	**Nephrologen und Dialyseschwestern**
Befragung:	**Persönliches <u>Interview</u> mit Rückfragemöglichkeit und Vorstellung des Kontextes**
Ziel:	**Befragung von 5+ Nephrologen aus (Uni-)Kliniken und Dialysezentren, sowie 5+ Dialysepflegekräfte**

IS-06: Fragebogen – Med01

ZENTRUM
FÜR
TELEMATIK E.V.

Allgemeine Fragen

Hier sollen allgemeine Wünsche und der Bedarf für Unterstützung ermittelt werden. Es geht NICHT darum die Arbeit von Menschen durch Technik zu ersetzen, sondern einfache, regelmäßige Tätigkeiten zu identifizieren, bei denen Sie unterstützt werden könnten. Bitte antworten Sie unabhängig davon, ob Sie die Idee für realisierbar halten. Ganz nach dem Motto: „wenn Sie drei Wünsche frei hätten, die Ihnen das Berufsleben vereinfachen sollen…“

1. Welche alltäglichen Arbeiten oder Arbeitsschritte könnten/sollten Ihrer Meinung nach automatisiert werden?
   (unabhängig von der Einschätzung der tatsächlichen Machbarkeit)

2. Wobei könnte ein technisches System Sie unterstützen?

3. Was sind alltägliche aber störende Tätigkeiten bei der Patientenversorgung?

4. Für welche Tätigkeiten/Entscheidungen wird unbedingt eine speziell ausgebildete Dialysepflegekraft benötigt?

5. Für welche Tätigkeiten/Entscheidungen wird unbedingt ein Nephrologe benötigt?

6. Wie könnte Ihre Arbeit sonst noch erleichtert werden?

Patientenstatus – Teil 1/2

Um das Befinden von Patienten zu beobachten stehen neben dem direkten persönlichen Kontakt auch eine Reihe messbarer Patientenparameter wie Puls, Blutdruck zur Verfügung. Stellen Sie sich vor: Alle technischen Hilfsmittel, wie Kamera, Mikrofon, PC, FAX, Telefon, Messgeräte und was Sie noch benötigen sei vor Ort gegeben. Ihr Patient befindet sich in einem anderen Zimmer, und Sie können nicht zu ihm gehen. Sie haben aber die Möglichkeit eine „dritte Person" zum Patienten zu entsenden um Sie anschließend über den Zustand des Patienten zu informieren.

7. Welche Messungen, Befragungen, Fotos, etc. würden Sie dann erfragen um den Zustand des Patienten beurteilen zu können?

8. Sie möchten bedrohliche Situationen des Patienten rechtzeitig identifizieren können. Sie möchten aber auch keinen unnötigen Aufwand betreiben. Wie oft sollten dann Ihrer Einschätzung nach die Informationen von der „dritten Person" aufgenommen und Ihnen berichtet werden?
    a. Gilt dies generell für alle Patienten?
    b. Welche bilden eine Ausnahme?

9. Welche Informationen befürchten Sie nicht messen lassen zu können?

10. Wäre Ihnen wohl bei der „Fern-Einschätzung" des Patienten?
    - Wenn nicht, warum?
    - Was fehlt Ihnen?

11. Angenommen der Patient kann sich schon selbst dialysieren, soll aber von Ihnen zusätzlich überwacht werden. Wann/Warum sollte dann die Informationen vom Patienten zu Ihnen gelangen? Wer sollte aktiv werden?
    a. Sollte der Patient Sie über seinen Zustand informieren können?
       → Der Patient fordert „dritte Person" auf Sie aufsuchen und zu informieren
    b. Soll auf Ihren Wunsch hin die „dritte Person" am Patienten die Daten sammeln?
       → Sie fordern die „dritte Person" auf den Patienten aufsuchen und informieren
    c. Sollten beide o.g. Möglichkeiten funktionieren?
    d. Genügt ein periodischer Rundgang der „dritten Person"?
        - Wenn ja, wie oft? (z.B. alle 30 Minuten)
    e. Welche der oben angesprochenen Möglichkeiten halten Sie für die wichtigste?

Patientenstatus – Teil 2/2

Sie sollen sich einen Eindruck vom Zustand des Patienten machen. Sie haben nun nur die Möglichkeit den Patienten durch einen Fragebogen, ein Telefonat oder ein Videotelefonat zu befragen.

12. Welche Fragen würden Sie den Patienten bitten in einem Fragebogen zu beantworten?

13. Was würden/könnten Sie in einem Telefonat erfragen?

14. Was könnte ein Videotelefonat eventuell für zusätzliche Informationen liefern, die Ihnen bei der Einschätzung des Patienten helfen könnten?

15. Wie würden Sie den Patienten am liebsten aus der Ferne befragen?

16. Was glauben Sie nur schwer einschätzen zu können, da Sie nicht direkt vor Ort beim Patienten sein können?

17. Glauben Sie, dass es möglich sein könnte sich ein realistisches „Bild“ vom Zustand des Patienten zu machen, auch wenn Sie nicht vor Ort sein können?

Dialysebewertung

Um die Dialysebehandlung und deren Erfolg einzuschätzen könnten Sie sich vieler Parameter bedienen.

18. Wer bewertet die Dialyse(qualität) im Zentrum?

19. Welche Parameter/Messungen benutzen Sie um daraus den Dialyseerfolg abzuleiten?

20. Wie gehen Sie vor um Langzeitverbesserungen oder -verschlechterungen des Patienten festzustellen?
    a. Welche Parameter/Messungen benötigen Sie hierfür?
    b. In welchen Zeitintervallen benötigen Sie die Daten jeweils?

21. Gibt es Ihrer Meinung nach Werte, die man noch nicht „messen" kann, die aber benötigt werden?

22. Gibt es „Faustformeln", „Eselsbrücken" oder „Näherungen" anhand derer man die Dialysequalität ableiten kann?
    - Nutzen Sie diese?
    - Was sind die wichtigen Faktoren?

23. Welche Daten/Parameter werden zwar während der Dialysebehandlung aufgenommen, zur Dialysebewertung aber nicht herangezogen?

24. Welche Daten sollte man zur Auswertung mittel- oder langfristig verwahren?

Appendix E

ARDS/ECMO questionnaire

Universitätsklinikum Würzburg
Klinik und Poliklinik für Anästhesiologie
Direktor: Univ.-Prof. Dr. Dr. h.c. Norbert Roewer
Leiter ARDS/ECMO-Zentrum: PD Dr. M. Kredel

ARDS Anamnesebogen

Notfallkontakt unter Telefon 0931 201-22222

Patientenname (Initialen): ____________ Alter: ____________ Klinik: ____
Geschlecht: ☐ männlich ☐ weiblich Ansprechpartner: ____________________________________
Körpergewicht: ___________________ Rückrufnummer: ____________________________________
Körpergröße: _____________________ Kostenträger: _______________________________________

Anamnese/Diagnosen:

Intensivstation seit: ______________________________________ Intubation seit: ____

Beatmung: Gerät: ____

☐ PCV ☐ VCV ☐ BIPAP ☐ andere: ________________ Beatmungsdauer: _____________ Lagerung: ___________________

PIP: __________ PEEP: ______ I:E: ________ AF: ________ AMV:_______ Vt:____________

FiO_2:__________ PaO_2: ______ $PaCO_2$:______ pH: ________ BE: _________ SaO_2/SvO_2: _______

Hämodynamik: Rhythmus: ____

HF: __________ MAP: ______ PAP: _______ ZVD: _______PCWP: ______ HZV: _______Temp:_________

Katecholamine:

Mikrobiologie:
Keimnachweis(e) ____________________ ☐ ORSA
Antibiose(n) ____________________________

Befunde:
Rö-Thorax/CT ____________________________
Thoraxdrainage(n) ____________________________
Pneumothorax ____________________________
Hautemphysem ____________________________
Neurologie ____________________________
TEE/Echo ____________________________

Labor:

GOT	________________	Leukos	________________
GPT	________________	CRP/PCT	________________
Bilirubin	________________	TPZ	________________
PCHE	________________	Thrombos	________________
Albumin	________________	Hb	________________
Krea	________________	Hkt	________________
Harnstoff	________________	Laktat	________________
Quick/ INR	________________	BZ	________________
PTT	________________	AT	________________

Nierenfunktion:
Diurese: ______________ Nierenversagen seit: _____________ Bilanz: _________________
Diuretika: ______________ CVVH seit: ______________________ Dialyse seit: _______________

Ernährung:
☐ parenteral ☐ enteral ☐ abgeführt am: ______________________

Therapieoptimierung:
☐ PEEP ☐ Dehydration ☐ Lagerung

Übernahme:
☐ Ja ☐ Rücksprache ☐ nein, wegen: ________________________
☐ Rückruf um/durch:

Stand: 04/2017

Datum: Name: Unterschrift:

Bitte übermitteln Sie den Bogen per E-Mail an **ards@ukw.de** oder per Fax an **0931 201-6022222**

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Glossary

AAL ambient assisted living. 21

AJAX Asynchronous JavaScript and XML. 75

AMS Adaptive Management and Security System. 125, 131, 140

ARDS acute respiratory distress syndrome. 160, 164, 165, 169, 209

CAT COPD Assessment Test. 21

CAT Complex Analysis Tool. 125–127, 134, 207

CBR case-based reasoning. 31

COPD chronic obstructive pulmonary disease. 4, 6, 21, 44, 45, 49–51, 53, 62, 63, 68, 109, 111, 115, 118, 121, 157, 159, 173, 177, 179, 206, 211

COTS commercial off-the-shelf. 3, 6, 43, 45, 49, 59, 61, 62, 71, 93, 173, 176, 178, 179, 181, 183

CPU central processing unit. 61, 62

CSS Cascading Style Sheets. 101

CSV comma separated values. 14

DSL digital subscriber line. 17, 19, 68, 72, 73, 84, 85, 88, 89, 206

DTLS Datagram Transport Layer Security. 80

ECG electrocardiogram. 11, 21, 62

EDGE enhanced data rates for GSM evolution. 68, 72, 73, 83, 85, 88

EPO Erythropoetin. 22

ESRD end stage renal disease. 22

FEV1 Forced Expiratory Pressure in 1 Second. 121

GOLD Global Initiative for Chronic Obstructive Lung Disease. 21

GPRS general packet radio service. 21, 65, 73, 83, 85, 88

GPS Global Positioning System. 88, 108

GSM Global System for Mobile Communications. 21, 88

GUI graphical user interface. 125

HD hemodialysis. 22–25, 205

HDP health device profile. 19, 62, 65, 72

HL7 Health Level 7. 14

HSDPA high speed downlink packet access. 17

HSPA high speed packet access. 73, 83, 85, 88

HTML HyperText Markup Language. 101, 125

HTTP HyperText Transfer Protocol. 72, 73

HTTPS HyperText Transfer Protocol Secure. 72, 73, 82

ICE Interactive Connectivity Establishment. 78, 79, 206

IMAP internet message access protocol. 76

IP internet protocol. 76

IPC Inter Process Communication. 126

IPv6 Internet Protocol Version 6. 76

ISDN integrated services digital network. 11

JS JavaScript. 101

LAN local area network. 78

LSF Least Square Fit. 132–134, 136, 138, 142, 144, 146, 149, 154, 208

LTE long term evolution. 19, 83, 85

MainTelRob Maintenance and Telematics for Robots. 123, 125, 128, 129, 131, 208

MB megabyte. 68, 129

Mbps Mega bit per second. 83

MDSS medical decision support system. 39

NAN Not a Number. 127

NAT Network Address Translation. 17, 74, 76, 78, 79, 206

PAN personal area network. 19, 48, 59, 71

PC Personal Computer. 71, 84–89, 167, 206

PD peritoneal dialysis. 22–25, 205

PLR packet loss rate. 20

POTS plain old telephone service. 11

QR . 130

RTT round trip time. 19, 20, 73, 83–91, 206, 207

SDP Session Description Protocol. 78

SMS short message service. 71, 72, 75, 76, 105

SpO2 . 109, 115, 116, 207

SPP serial port profile. 19

SQL Structured Query Language. 131

SRTP Secure Real-time Transport Protocol. 80

SSL Secure Sockets Layer. 16, 73

STUN Session Traversal Utilities for NAT. 78

TARDIS Telemedical Applications with Rule based Decision- and Information-Systems. 6, 97, 98, 100, 103, 106, 107, 111, 112, 115, 123, 125, 126, 129, 130, 134–140, 142, 146, 152, 164, 170, 176, 207, 209

TCP Transmission Control Protocol. 92, 93, 207

TEN-HMS "Trans-European Network-Home-Care Management System". 37, 38, 205

TIM-HF "Telemedical Interventional Monitoring in Heart Failure". 37

TLS Transport Layer Security. 16

TURN Traversal Using Relays around NAT. 78

UDP User Datagram Protocol. 17, 20, 74, 84, 92, 93, 205, 207

UMTS universal mobile telecommunication systems. 17, 19, 65, 68, 71–73, 83, 85, 88

UPNP Universal Plug and Play. 76

VCP Visual Control Point. 127, 130, 131, 139, 140, 149, 150, 208

VCPs Visual Control Points. 128, 130, 131

VPN virtual private network. 92

WAN wide area network. 17, 48, 59, 68, 71, 72

WebRTC Web Real-Time Communication. 77, 78, 80, 82, 206

WiFi WiFi is a technology that allows to connect devices via wireless LAN. 17, 65, 68, 71, 72, 84, 85, 88, 89, 206

XML eXtensible Markup Language. 15, 103, 106

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